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RESISTOJECT: ENGINEERING MODEL
FABRICATION AND TEST TASK Summary
Report (TRW Systems Group) 76 p HC

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MONOPROPELLANT HYDRAZINE RESISTOJET

ENGINEERING MODEL FABRICATION AND TEST TASK SUMMARY REPORT

**TRW SYSTEMS GROUP
ONE SPACE PARK
REDONDO BEACH, CALIFORNIA 90278**

MARCH 1973

**Prepared for
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND 20771**



TRW
SYSTEMS GROUP

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Prepared by Charles K. Murch Approved by Dennis Asato
Charles K. Murch Dennis Asato

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FOREWORD

This is the fourth Task Summary Report submitted under Contract NAS5-11477, "Design, Development, and Testing of an Engineering Model 20-Millipound Thrust Monopropellant Hydrazine Resistojet." The program originated in the Auxiliary Propulsion Branch of the NASA/Goddard Space Flight Center. Mr. Dennis Asato is the Technical Officer for NASA/GSFC. Mr. Charles K. Murch is the Project Manager for TRW Systems and is also the principal contributor to this report.

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1. SUMMARY

The Monopropellant Hydrazine Resistojet, termed the Electrothermal Hydrazine Thruster (EHT) by TRW Systems, thermally decomposes anhydrous hydrazine propellant to produce a high-temperature, low-molecular-weight gas for expulsion through a propulsive nozzle. The EHT developed for this program required about 3-5 watts of electrical power and produced 0.020 to 0.070 pound of thrust over the inlet pressure range of 100 to 400 psia. The thruster was designed for both pulsed and steady state operation.

The objectives of the Engineering Model Fabrication and Test task of the program included the performance characterization and life testing of a flight-type EHT. To remain within cost and schedule constraints and to reflect more realistic thruster performance requirements, GSFC modified the life test specifications. The modified life test goals of 300,000 pulses and 30 hours of steady-state operation on a single thruster were successfully met. A summary of the GSFC original requirements and GSFC modified requirements, and the performance of the Engineering Model EHT is given in Table 1-1.

This document describes the experimental program leading to the Engineering Model EHT design, modifications necessary to achieve the required thruster life capability, and the results of the life test program. Other facets of the program, including analyses, preliminary design, specifications, data correlation, and recommendations for a flight model are discussed in Task Summary Reports.

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*See Section 3, this document.

**Original Life Test Requirements:	Cycle Life	10^6 cycles
	Steady State Life	30 hrs

2. THRUSTER DESIGN AND FABRICATION

2.1 Preliminary Design

The preliminary design of the EHT and the performance requirements established by GSFC were presented in Monopropellant Hydrazine Resistojet, Preliminary Design Task Report, TRW Document 20266-6009-R0-000, February 1972. Figures 2-1 and 2-2 show the preliminary design EHT in a cutaway view and assembled with a Parker HPM valve. Figure 2-3 is a photograph of the unit. The thrust chamber, fabricated from Haynes 25 material, had inside dimensions of about 0.2-inch diameter by 0.5-inch long and contained a composite platinum/Haynes 25 screen. The nozzle was of conventional convergent-divergent design with an expansion half-angle of 15 degrees and an area ratio of 50. The thruster was heated by a double-wire tubular element wrapped around and braced to the cylindrical portion of the thrust chamber. The heater was comprised of Nichrome V resistance wire, magnesia insulation and an Inconel sheath. The differential swaging process used in fabricating the heater resulted in a smooth, junction-free transition between the heater leads and the resistance wire. The barrier tube was designed to minimize conductive heat transfer from the thrust chamber to the solenoid valve and to provide structural support for the thruster. The injector, positioned concentric to the barrier tube, was fabricated from Haynes 25 capillary tubing. The injector had a bend in it to prevent undue thermal stresses. The injector-to-valve seal was accomplished with a threaded fitting and a Teflon compression seal. Particular care was taken to eliminate excess volume between the valve seat and the thrust chamber in order to minimize thrust response times.

The insulation package was molded from a fibrous refractory material and machined to its final shape. The insulation was retained on the thrust chamber by a spot-welded nickel ribbon. The total weight of the insulation package was less than 0.01 pound.

For test purposes, the chamber was instrumented with thermocouples and a pressure transducer. The thrust chamber assembly shown in Figure 2-1 weighed 0.04 pound. The complete assembly shown in Figure 2-2 weighed less than 0.26 pound.

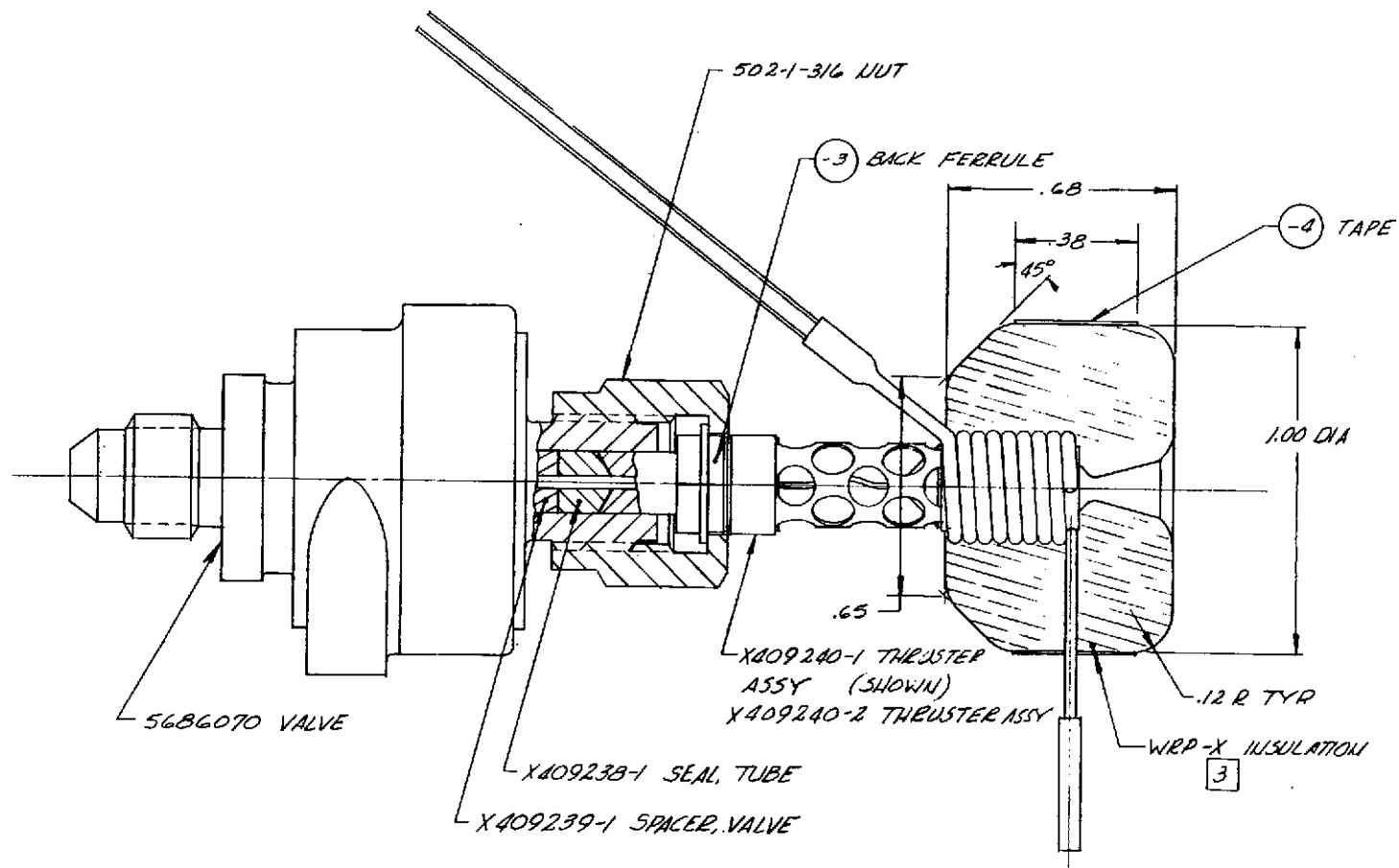


Figure 2-2. Preliminary Design EHT Assembly

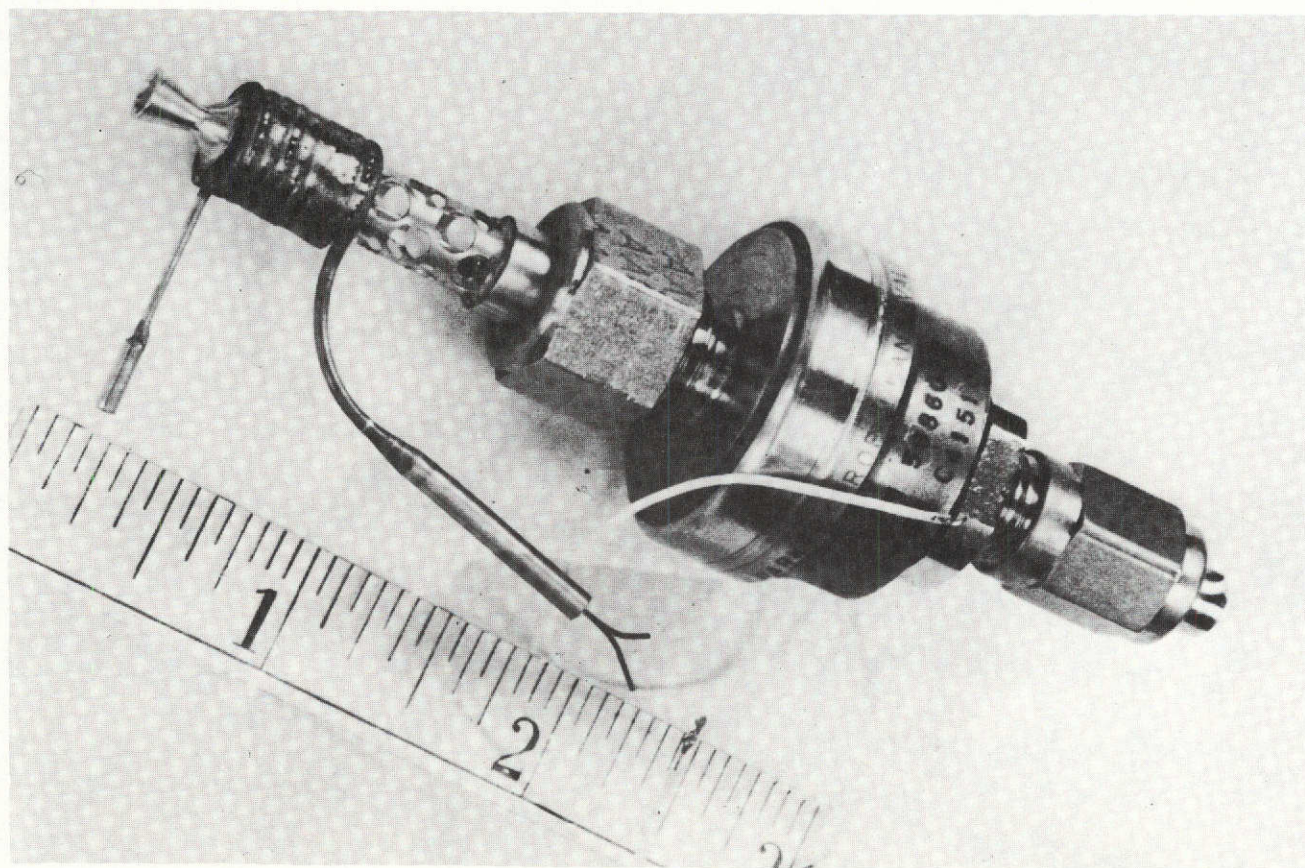


Figure 2-3. Preliminary Design Thruster (Without Insulation Package)

2.2 Configuration Variation Thruster Design

A second thruster configuration was tested extensively in support of the Engineering Model thruster effort. The preliminary design thruster produced about 210 seconds specific impulse and operated at a steady state temperature of about 1550°F. One of the preliminary design thrusters was fabricated with a platinum screen pack. Tests of this unit showed a somewhat surprising performance improvement — specific impulse increased to about 230 seconds and the steady state temperature increased to about 1800°F. The design shown in Figures 2-4 and 2-5 was fabricated to investigate the effects of screen pack geometry on thruster performance.

The internal geometry of the Configuration Variation Thruster was identical to the preliminary design unit shown in Figure 2-1. A threaded nozzle was used to allow access to the screen pack without destroying the unit. The external surface of the nozzle was shaped square to allow the use of a special wrench for disassembly. A copper gasket provided the nozzle-to-chamber seal. A number of different screen pack geometries were tested with this unit. These geometries included:

- a) The baseline screen pack geometry shown in Figure 2-1.
- b) A screen pack with a second Haynes 25 screen at the upstream end of the pack. This was done to prevent the bulging of the screen during the assembly cycle.
- c) A shorter screen pack which provided a larger head space.
- d) Platinum screen packs of varying density.

The results of these tests are discussed in a later section.

2.3 Engineering Model Design

Near the end of the Preliminary Design Phase of the EHT program, the program was redirected toward meeting the requirements and interfaces applicable to the ATS-F&G propulsion subsystem. This redirection resulted in changes in the solenoid valve selection, the insulation package, and the mechanical and thermal interfaces. This new design was designated the Engineering Model (EM) thruster.

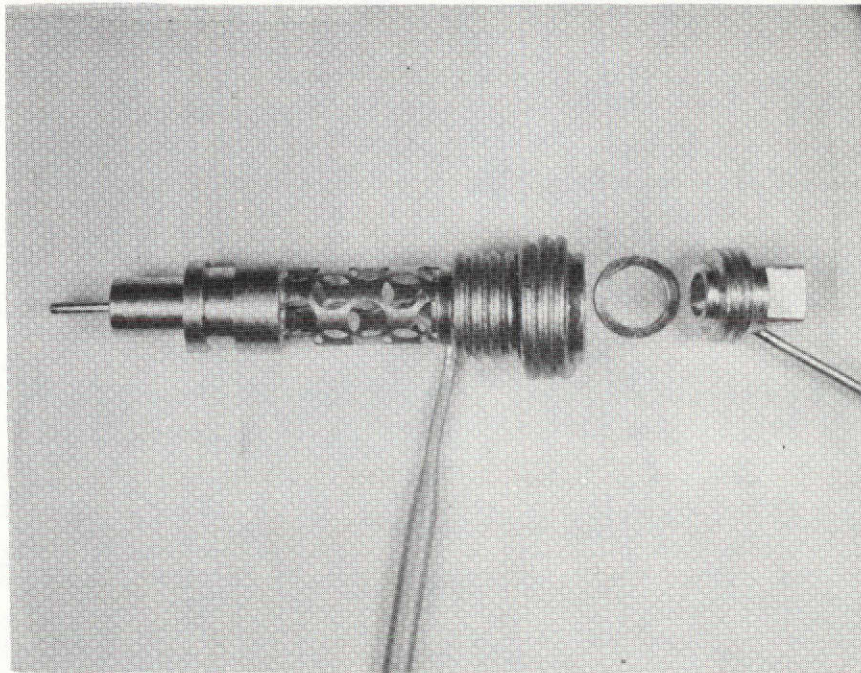


Figure 2-4. Configuration Variation Thruster (Disassembled)

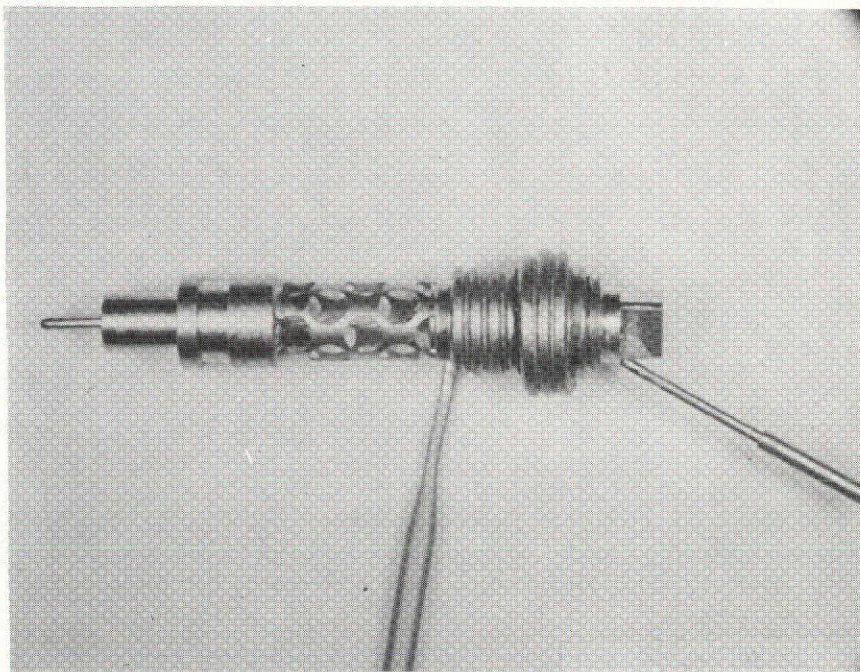


Figure 2-5. Configuration Variation Thruster

2.3.1 Solenoid Valve and Flow Restrictor

The solenoid valve used with the EM/EHT was the same as those used on the ATS-F&G propulsion system. The valve (Parker-Hannefin Part Number PTS-5700060-103) is shown in Figure 2-6. The seal and solenoid configuration is coaxial and the inlet line is at 90 degrees to the axis. The moving portion of the valve is a clapper-type arrangement loaded by a Belleville spring. A spring-loaded disc in the center of the clapper seals against a Teflon ring swaged into a groove near the valve outlet. The valve incorporates an entrance filter and EMI-suppression diodes. A three-bolt partial flange was used to mount the valve to a bracket and also to load the compressive seal between the valve outlet and the thruster injector.

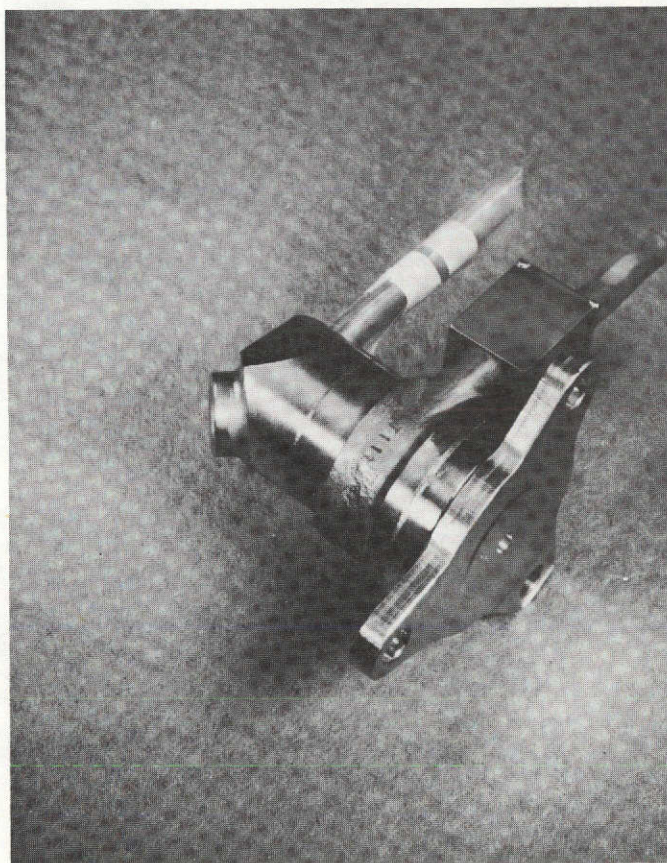


Figure 2-6. Parker Valve

The operating characteristics of the ATS-F&G valve are nearly identical to those of the Parker half-HPM valve (Figure 2-3) used throughout the development of the EHT. Valve power is less than 3 watts at 28 volts. Opening and closing response times amount to about 6-10 and 6-8 milliseconds, respectively, over the nominal voltage range of 24.7 to 28.1 vdc. The valve weighs 0.53 pound.

A Lee Company Viscojet was used immediately upstream of the solenoid valve as a flow restrictor. This device is shown in Figure 2-7. The Viscojet provides a 40 psid pressure drop at the rated flow of 0.00045 pound per second of hydrazine. This corresponds to a Lohm rate of 38,200. However, with the lower EHT flow rates, the pressure drop was calculated as 8 psid. With the EHT, this model Viscojet served essentially no function other than conforming to the ATS-F&G interfaces.

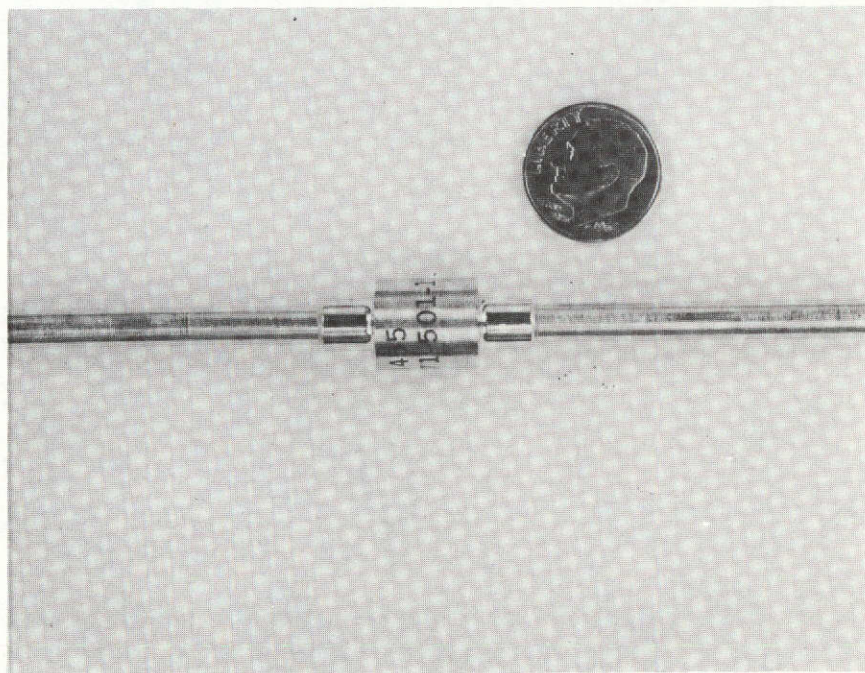


Figure 2-7. Lee Viscojet

2.3.2 Thrust Chamber Assembly

The thrust chamber assembly was comprised of the chamber, the nozzle, the screen pack, injector, barrier tube and support post. These units are shown in Figure 2-8. The support post length was determined by the ATS-F&G interfaces. One end of the post was brazed to the thruster bracket; the other end was brazed to the barrier tube. The upstream end was configured to accommodate the compression seal to the valve. The barrier tube supported the thrust chamber and also limited heat transfer from the chamber to the support post/bracket/valve assembly.

The injector was a 1.2 inch long tube with a nominal inside diameter of 0.005 inch and an outer diameter of 0.014 inch. Inconel 600, Haynes 25, and Pt-10Ir were tried as injector material with various degrees of success. The upstream end of the injector was inserted inside the solenoid valve to limit the excess volume between the valve seal and the chamber, and the downstream end of the injector was brazed to the chamber. The injector/chamber braze joint was designed to limit the thermal conduction across it. Inconel 600 material was initially chosen for the injector on the basis of

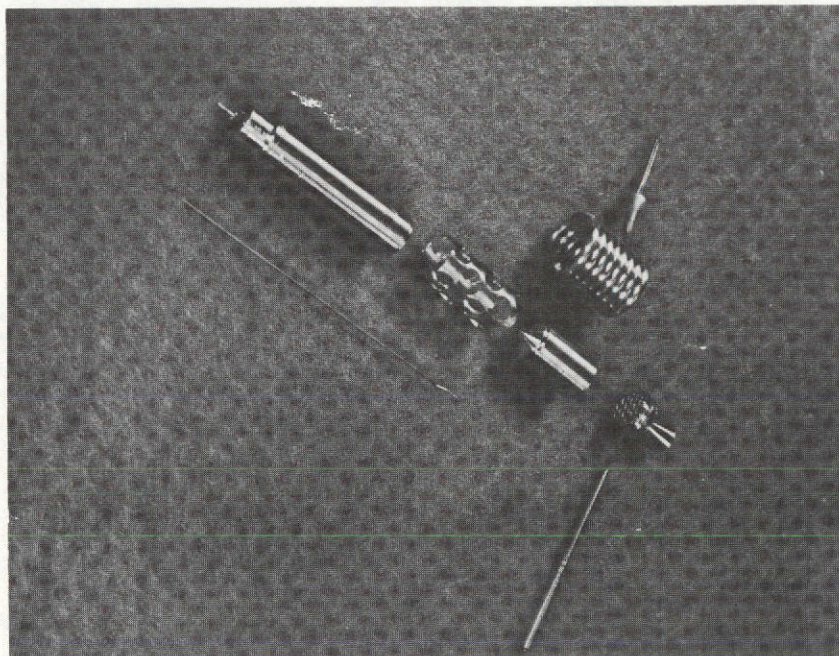


Figure 2-8. EM/EHT Components

of compatibility tests conducted for another TRW program. Although Haynes 25 material initially appeared more suitable on the basis of compatibility with hydrazine, it proved more catalytic to hydrazine decomposition when used with the EHT.

The thrust chamber itself remained relatively unchanged from the preliminary design. As indicated in the figure, the heater lead section was shortened so that it could be enveloped by the insulation package.

The nozzle characteristics remained unchanged. The throat diameter was 0.018 inch and the expansion area ratio was 50. The nozzle incorporated a hole for the pressure tap tubing as shown in Figure 2-1. Both the nozzle and the chamber were fabricated from Haynes 25.

The screen pack density was increased by about a factor of two relative to the preliminary design resulting in smoother operation. The screen pack was fabricated from platinum gauze and Haynes 25 mesh.

2.4 Engineering Model Fabrication

Views of a fully assembled foreshortened unit are given in Figures 2-9 and 2-10. The unit is considered to be a flight configuration with two exceptions, a chamber pressure tap and a split outer can, which were incorporated to aid in the Engineering Model test. The pressure tap was included since thrust chamber pressure is a key diagnostic parameter. For flight, the pressure tap would be deleted entirely or else crimped, cut off, and welded closed after acceptance testing. The outer can was designed as a split cylinder with a removable end plate to allow a quick method of disassembly for installation of thermocouples and for post-test examination. A flight unit would employ a simpler design, perhaps welded in place.

Fabrication of the piece parts shown earlier in Figure 2-8 was accomplished with conventional machining techniques and electrical-discharge machining. The screen shown attached to the nozzle was a 40 x 40 mesh Haynes disc which was spot welded to the nozzle. This screen served as a support for the stacked platinum screens shown in Figure 2-11. Also shown in the figure is the punch used to cut the screen into discs and a compression tool. The discs were stacked into

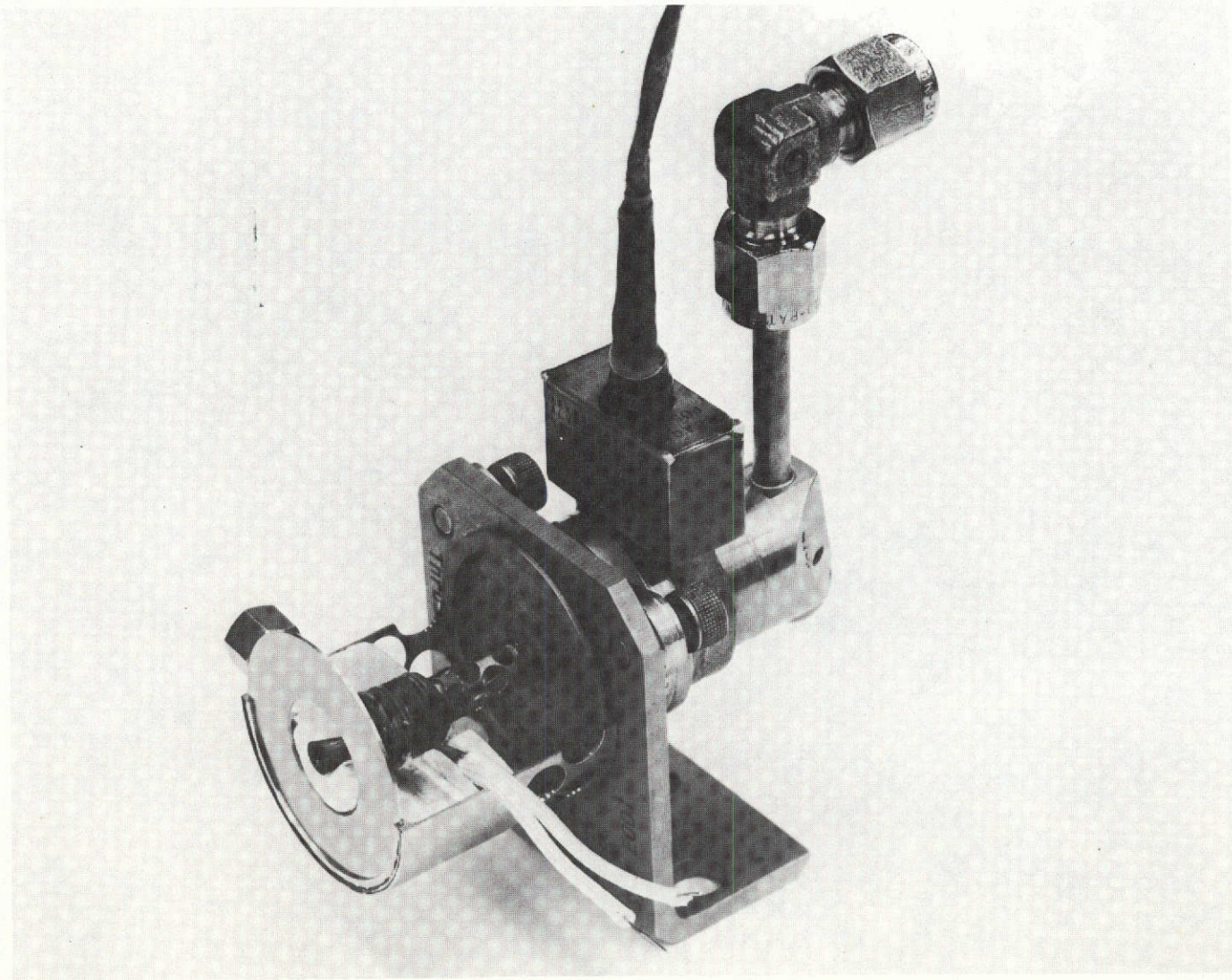


Figure 2-9. Engineering Model Thruster

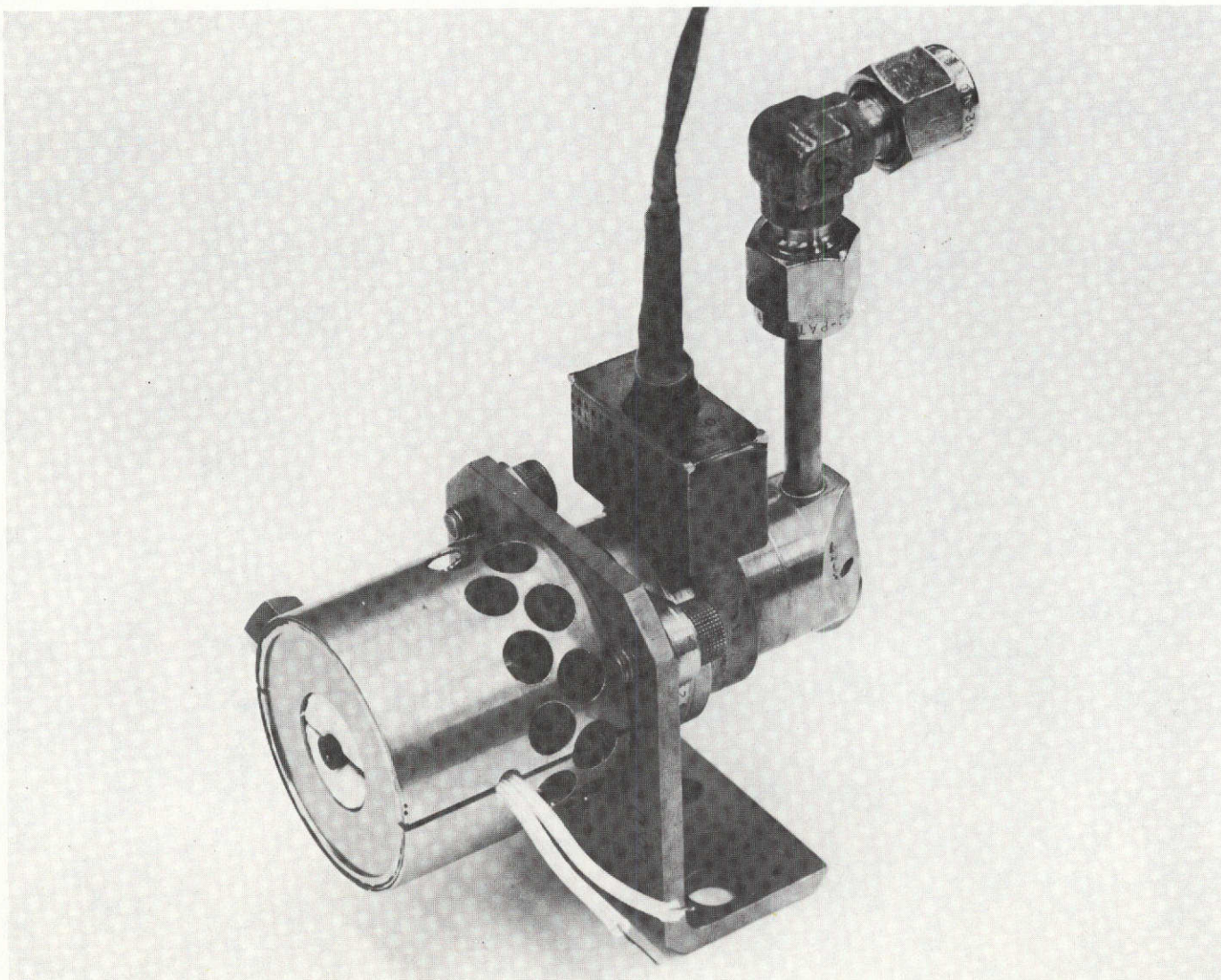


Figure 2-10. Engineering Model Thruster

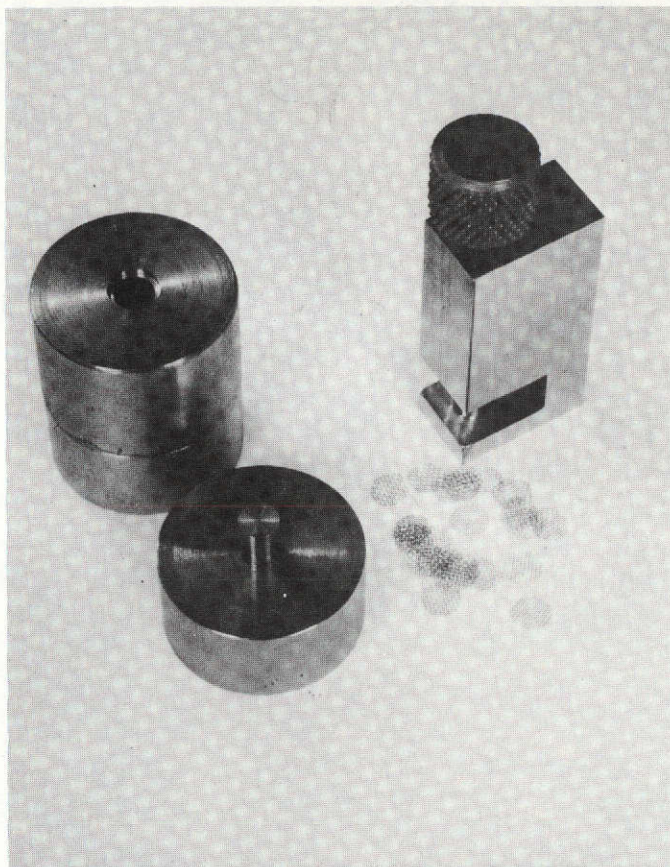


Figure 2-11. Screen Forming Tooling

the tool and compressed to about 50 percent of their unloaded height. The Engineering Model thruster used 60 screens. The compressed screen pack was transferred directly from the tool to the thruster chamber.

The heater elements were formed with the tooling shown in Figure 2-12. The heater was about 18 inches long and wound in two layers. The first layer was wound around the right-hand post in Figure 2-12. The sleeve shown in the bottom of the photo was placed over the first layer and the second layer was then wound on this sleeve. The unit was clamped in place on the tool, the sleeve was removed, and a braze "stop-off" was applied to the heater and tool. To prevent "springback" when the heater was removed from the tool, the heater unit was subsequently annealed.

The first Engineering Model thrusters were built with a thermal relief bend in the injector. For reasons to be discussed later, the design was changed to incorporate a complete loop. The injector forming tool is shown in Figure 2-13. The chamber end of the injector was trimmed square and deburred on a jeweler's lathe.

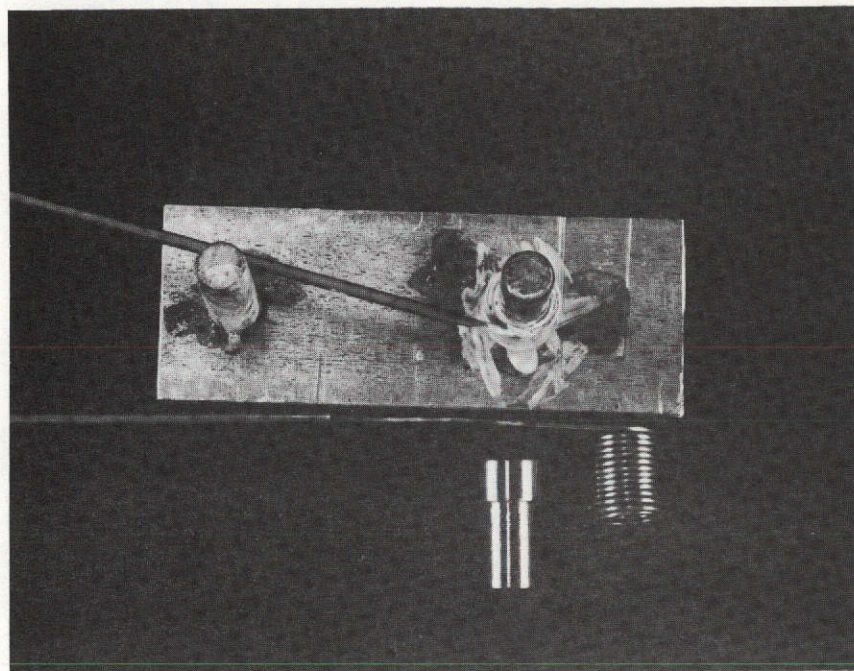


Figure 2-12. Heater Forming Tool

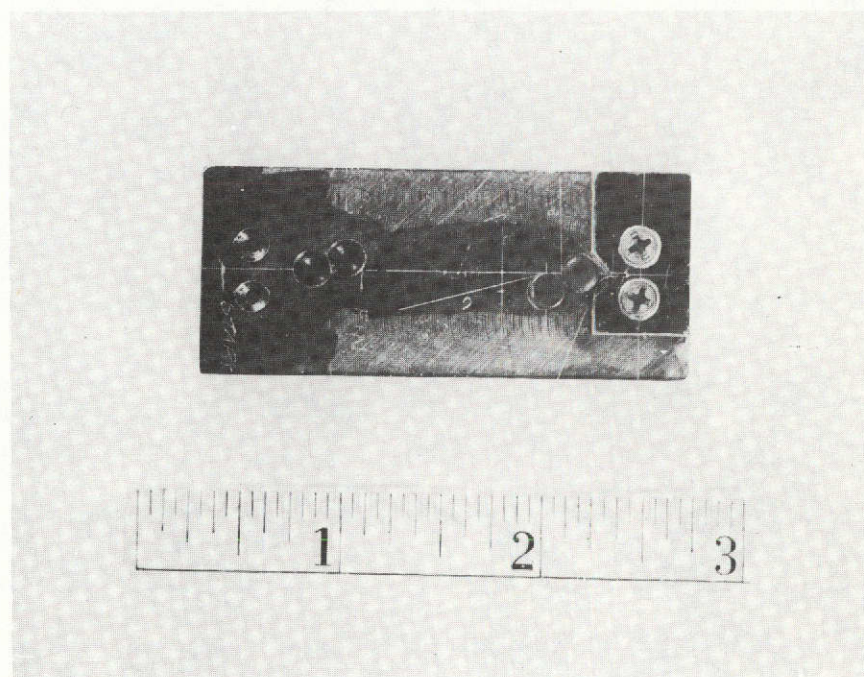


Figure 2-13. Injector Forming Tool

The insulation package was formed from WRP-X, a material which is procured in the form of a thin, wet felt. This material was wrapped around a split aluminum mandrel as shown in Figure 2-14. The insulation was then cured in an oven and the outer contour was machined to shape. A jeweler's saw was used to split the insulation using the mandrel slot as a guide. Clearance slots for the heater and chamber pressure tap were made with a small file.

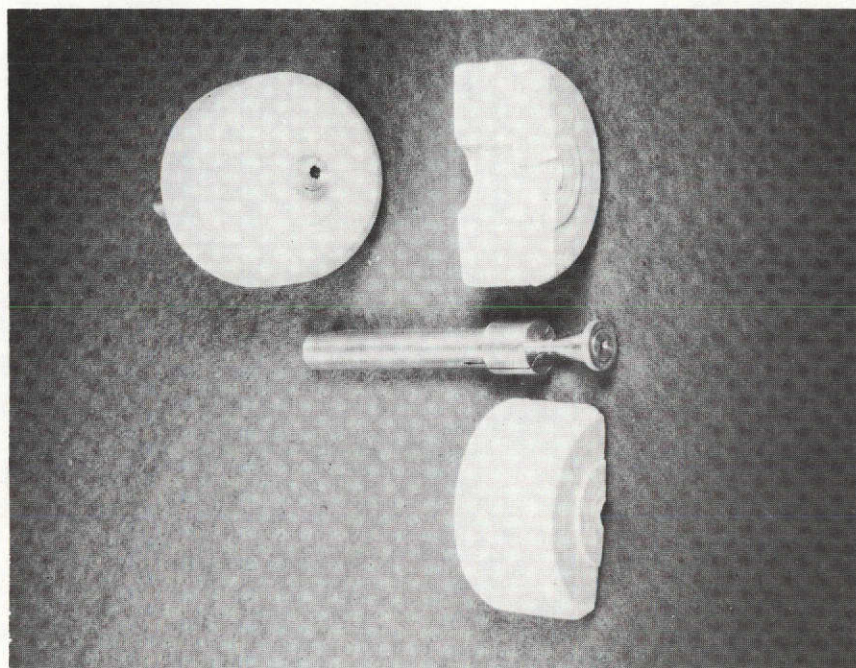


Figure 2-14. Insulation Tooling

The thruster was brazed together in three separate cycles using braze alloys with progressively lower melting temperatures. The highest temperature (and most critical) braze was that which joined the chamber to the injector. This braze was made first. An example of this braze joint, which proved to be quite troublesome, is shown in Figure 2-15.

The next braze cycle, carried out at a slightly lower temperature, was used to join the nozzle, chamber pressure tap, heater, barrier tube, and support post. The support post/bracket joint was made with a third braze cycle.

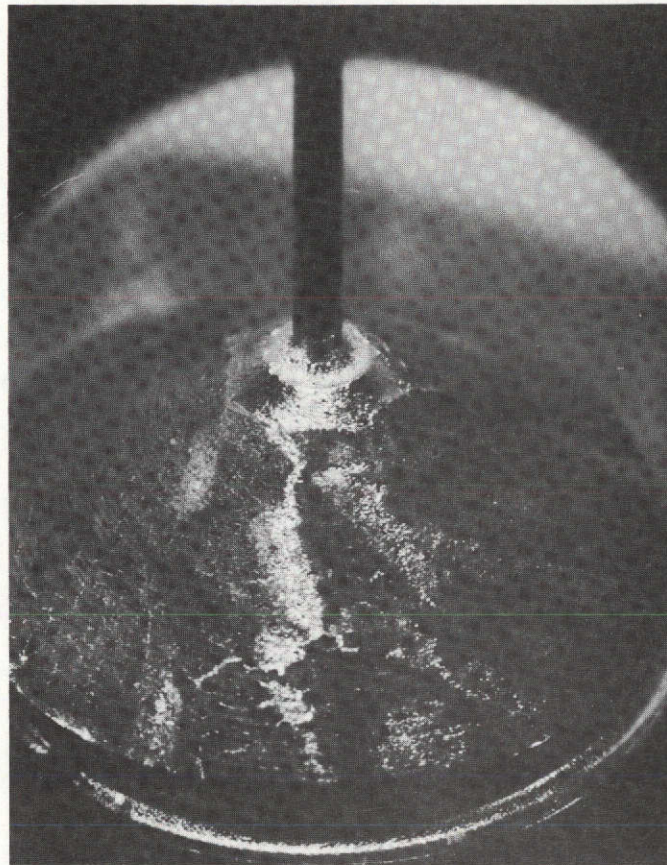


Figure 2-15. Injector/Chamber Braze

Following installation of the valve, the thruster was instrumented with thermocouples as shown in Figure 2-16. (Comparison of Figures 2-9 and 2-16 shows that two different EM thruster configurations were built. The primary difference was in the length of the support post, which also necessitated a change in the length of the outer can.)

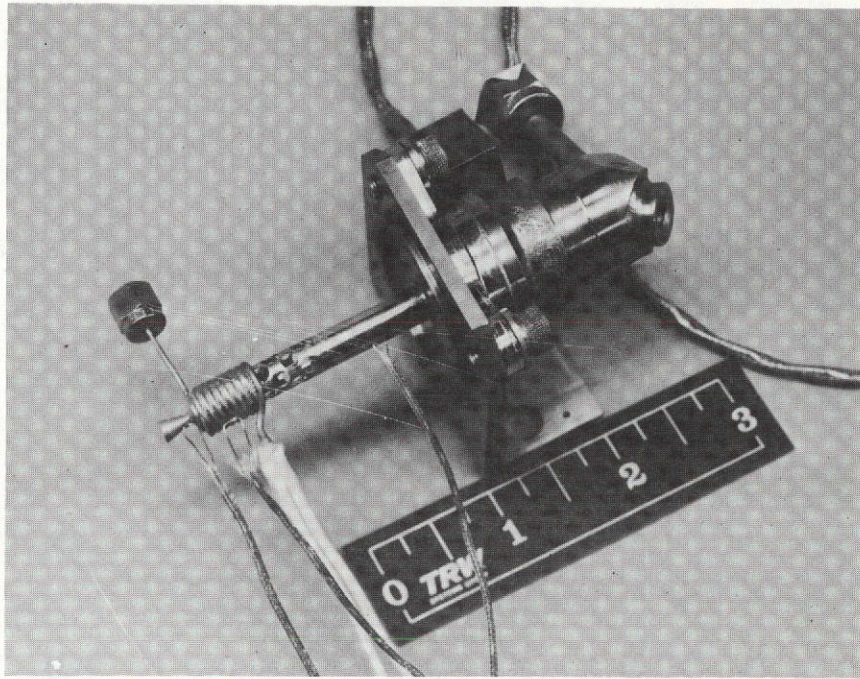


Figure 2-16. Instrumented Chamber Assembly

3. PRELIMINARY TEST PHASE

The Analysis and Preliminary Design Tasks, together with the supporting test efforts, resulted in a design which appeared capable of exceeding all of the GSFC performance requirements. In addition, a successful 10^6 cycle development test indicated that the cycle life capability requirements could be easily met.

However, some questions remained relative to thruster-to-thruster performance reproducibility. Thrust level, for instance, was found to vary about 6 percent under identical conditions for two apparently identical thrusters. Pulse-mode performance also varied. Some of the units produced nearly ideal pulse shapes while others, without any evident technical reason, produced pulse shapes with long tail-off times or chamber pressure depressions in the steady-state portion of the pulse. In order to gain some insight into the geometrical influence on performance, the "work-horse" thruster described in Section 2.2 was tested extensively.

The Engineering Model design that resulted from the preliminary tests and analyses was designed, fabricated and tested. Several failures were experienced with the first few EM thrusters. These failures were related to materials and fabrication problems. The solutions to these problems are discussed in this section. Changes resulting from the evaluation of these failures were incorporated into the EM thruster design and all of the performance and life capability requirements were successfully met. The results of the performance and life capability tests are described in Section 4.

3.1 Preliminary Million Cycle Life Test

As stated earlier, a cycle life test was conducted using development hardware. The thruster used for this test is shown in Figure 3-1. This design used a coaxial injector within a larger supporting tube. The tube visible in the photo is a thin-walled stainless steel tube brazed to the valve flange and chamber head end. The inside diameter of this tube was about 0.020 inch. Inside of the stainless steel tube was a platinum injector with an outside diameter of 0.015 inch and an inside diameter of 0.005 inch. The inner tube was brazed to the outer tube only at the

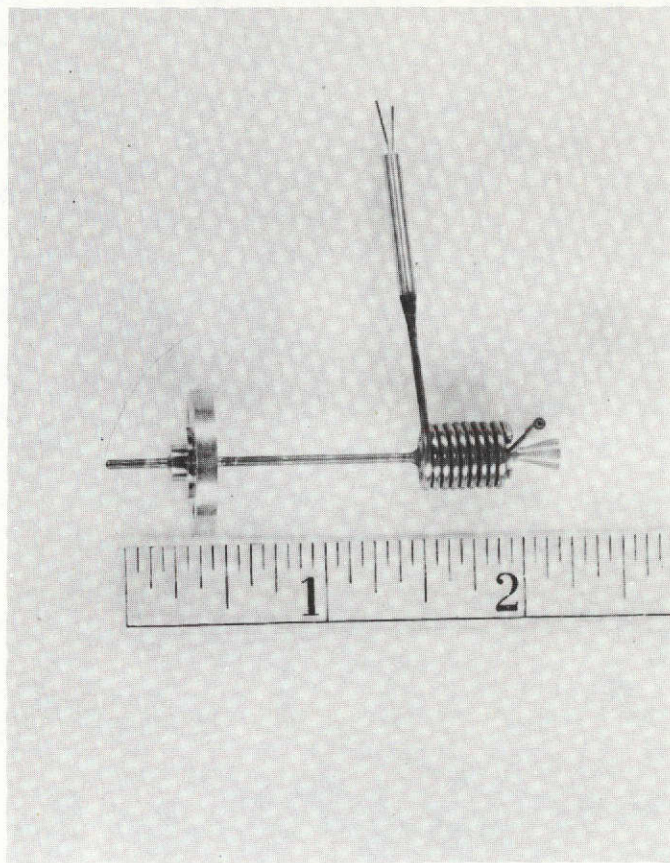
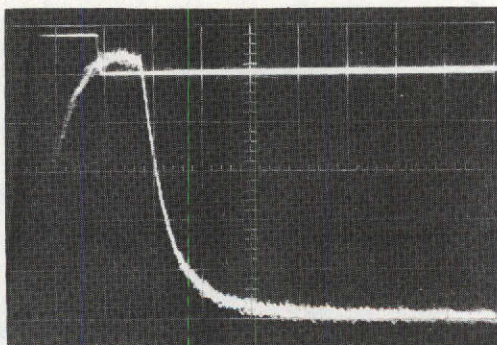


Figure 3-1. Development Thruster

entrance end; the inner tube was unsupported for virtually its entire length. This thruster was designed to be supported by the insulation package. Analysis of this design eventually led to the barrier tube-type mounting shown earlier in Figure 2-3.

Figure 3-2 shows some of the data taken during the 10^6 cycle test. Each figure is an overlay of 10 to 20 consecutive chamber pressure traces taken at different times during the test. For all 10 photos, most of the test parameters were identical. The electrical pulse width was 0.030 second and the OFF time was 0.470 second. The thruster inlet pressure was 100 psia. Because a wide range of operating conditions were incorporated in the test, the thruster operating temperature was not entirely consistent from test to test. This variability in temperature accounts for some of the change in pulse shape and response times. At 200 pulses, the thruster was relatively cool and produced rapid rise times to steady state. In all subsequent photos, the injector temperature was quite high



200 Pulses

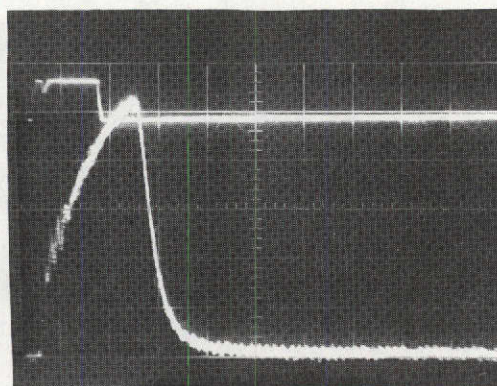
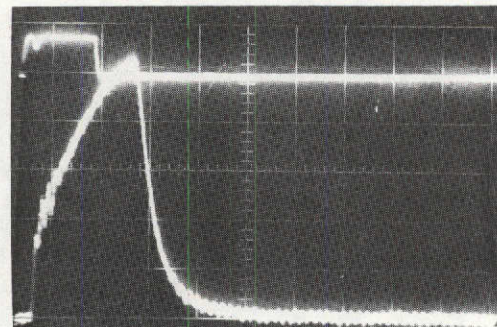
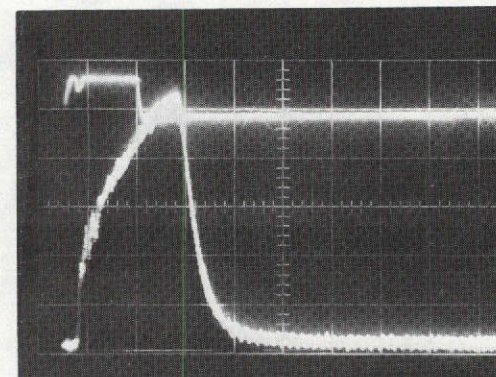
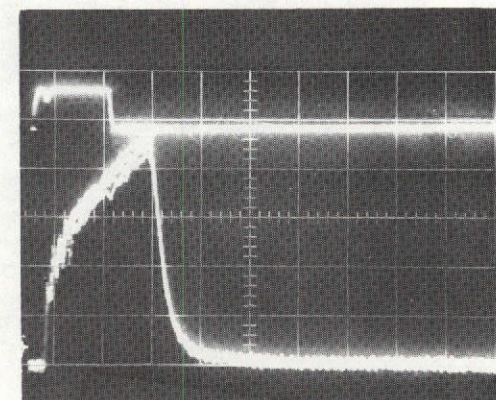
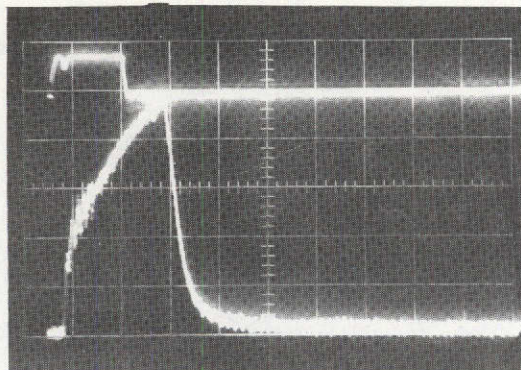
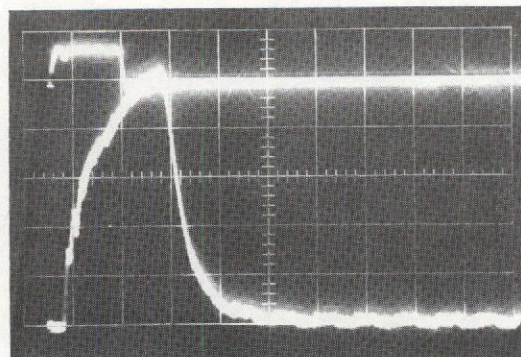
110,000
Pulses150,500
Pulses202,500
Pulses259,100
Pulses

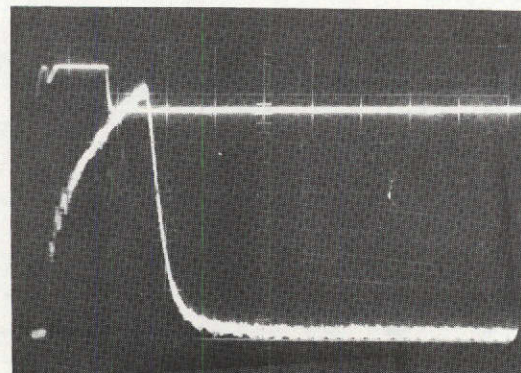
Figure 3-2. Cycle Life Data



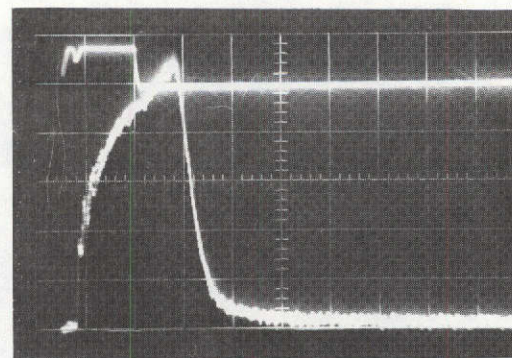
307,000
Pulses



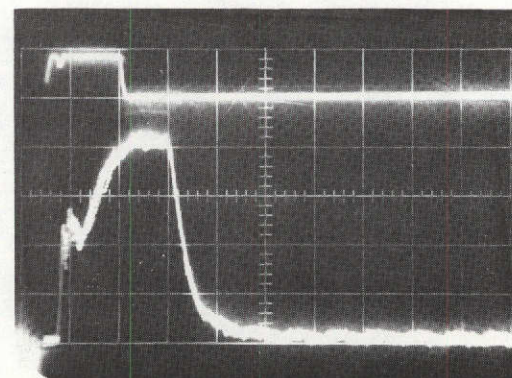
356,000
Pulses



52300 Pulses



701,000
Pulses



1,001,400
Pulses

Figure 3-2. Cycle Life Data (Continued)

and the thrust rise times were relatively long. High injector temperatures were found because partial vaporization of the propellant and an attendant increase in pressure drop. This was a design deficiency for the unit tested and has since been corrected. In the final photo, taken at 1,001,400 cycles, the initial transient has a spike in it. This spike has been observed in other thrusters and is attributed to propellant vaporization in the injector and subsequent quenching. As mentioned before, this problem was corrected by a thermal redesign of the propellant injector.

Several significant conclusions were drawn from this test. A cycle life capability three times greater than the modified GSFC requirement was demonstrated. Based on the integrated area under the chamber pressure curves, the delivered impulse bit variation was less than ± 15 percent over the 10^6 cycles. Some of the variation is attributed to non-reproducibility of test conditions and measurement errors. The shift in the pulse centroid was very small, amounting to less than 5 milliseconds. Finally, no evidence of injector plugging was observed upon disassembly of the thruster. The test was conducted with mil-grade hydrazine. A propellant analysis is given in Table 3-1.

3.2 Configuration Variation Tests

Two thrusters of the design shown in Figures 2-4 and 2-5 were fabricated. These thrusters were identical except one unit had a Haynes 25 injector and the other was built with an Inconel 600 injector.

The unit with the Haynes injector included a screen pack composed of 37 platinum gauze screens as shown in Figure 2-11. With an inlet pressure of 100 psia, the unit produced 0.029 pound of thrust at a specific impulse of about 200 seconds. The chamber temperature and low specific impulse indicated that not all of the propellant was being decomposed. This condition in which liquid exits the propulsive nozzle is termed "flooding" and indicates an inadequate thruster design.

To verify that flooding had indeed occurred, a test was conducted at atmospheric pressure rather than at vacuum conditions. The presence of a visible exhaust plume verified the assumption of flooding.

Table 3-1. Propellant Analysis for Million
Cycle Test

	<u>% Weight</u>	<u>PPM</u>
N_2H_4	99.21	
H_2O	0.33	
$CO_2 + NH_3$	0.33	
Unidentified (C_XF_X)	0.13	
Non-Volatile Residue		<u>23.2</u>
Cu		0.3
Fe		2.3
Zn		0.4
Mg		0.3
Al		3.0
Na		Present
K		2.5
Ca		1.6
Ni		0.6
Chloride		9.6

Flow patterns within the screen pack were altered by spot welding a 0.070 inch diameter Haynes 25 disc to the lower retainer screen. This "stagnation plate" geometry has been used on several catalytic thruster designs. By creating a stagnant region near the downstream end of the screen pack, the propellant flow is diverted through an annular space near the nozzle entrance. This effectively increases the length of the screen pack. Tests with this configuration indicated a slight performance improvement — specific impulse was increased to about 210 seconds.

The same thruster configuration was retested with a slightly larger nozzle diameter. During this test, it was noted that the injector end of the thruster was cooling off when propellant was admitted. This indicated that the propellant decomposition was occurring within the screen pack rather than in the head space. Disassembly of the thruster indicated that the first few upstream screens had bowed up into the head space and thereby had altered the internal geometry.

Several tests were conducted using a single Haynes 25 screen to support the upper end of the screen pack to prevent the bowing up into the head space. The presence of the Haynes 25 screen at the point of propellant impingement seemed detrimental to the thruster performance. Measured values of specific impulse varied from about 190 to 210. Varying the head space volume and screen pack length was also ineffective.

At this time, the fixture shown earlier in Figure 2-11 was built to allow the platinum screens to be compacted prior to insertion into the chamber. This tool allowed more screens to be compacted into a given stack height and also produced a more structurally sound screen pack without the use of a Haynes 25 support screen at the upstream side. An experimental evaluation indicated that a compacted stack of about 60 screens was near optimum and resulted in delivered steady-state specific impulse values in excess of 215 seconds for the entire inlet pressure range. This geometry was selected for the EM thruster.

3.3 Insulation Tests

A sequence of tests was conducted to determine the no-flow heat loss characteristics of the thruster with the WRP-X insulation. Three thrusters with different geometries were tested as shown in Figure 3-3. The unit

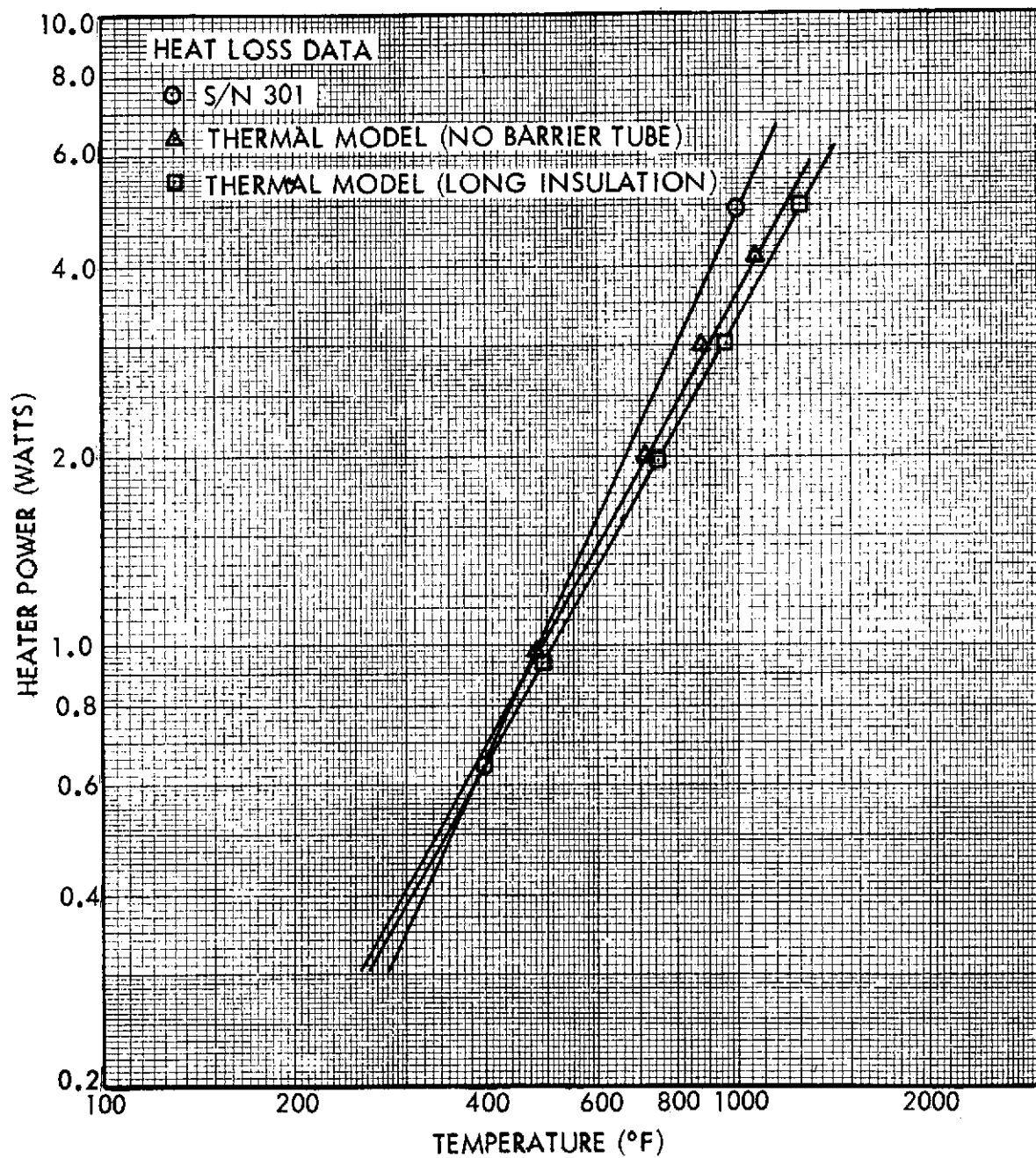


Figure 3-3. Heat Loss Test Data

marked S/N 301 was of the standard configuration, with a barrier tube and an insulation package which did not cover the head end of the thruster. The thermal model thruster had no barrier tube and was tested with two different insulation packages; one covered the head end of the thruster and the other allowed the head end to radiate to the valve bracket. These tests indicated that the requirements for 5 watts maximum could be easily met. The standard configuration with the barrier tube reached 1000°F at 5 watts. The more optimum but less practical, configuration reached 1000°F with about 3 watts.

3.4 Preliminary Tests with Engineering Model Thrusters

The preceding sections have discussed the design of the Engineering Model (EM) thruster and the tests which were conducted in establishing the design. This section describes a series of tests which uncovered a design deficiency and several problems relating to materials. The thruster tests described in this section were performed to meet the steady state and cycle life requirements listed on Table 1-1. The preliminary tests of the Engineering Model Thrusters were performed predominantly at a very rapid pulse rate of 10 pulses per second with a 25 millisecond command pulse width to minimize test time. Results of these tests seemed to indicate that this severe pulse rate and its corresponding injector temperature contributed significantly to the materials problem. The subsequently successful Engineering Model Thruster cycle test was performed at a more reasonable average rate of 2 pulses per second with a 25 millisecond command pulse width.

3.4.1 Thruster S/N GSFC-001

Based on the results of earlier tests, Inconel 600 appeared to be the best choice for the injector material for the EM thrusters. The pulsing characteristics of the thrusters with Inconel injectors appeared superior to those with Haynes 25 injectors. The injector was fabricated with a bend in it at about the mid-point as shown in Figure 2-1. The screen pack was comprised of 60 platinum gauze discs. Figures 2-10 and 2-11 show the completed unit.

Steady state tests (Figure 3-4) indicated that the overall performance was satisfactory, so a series of characterization tests was initiated.

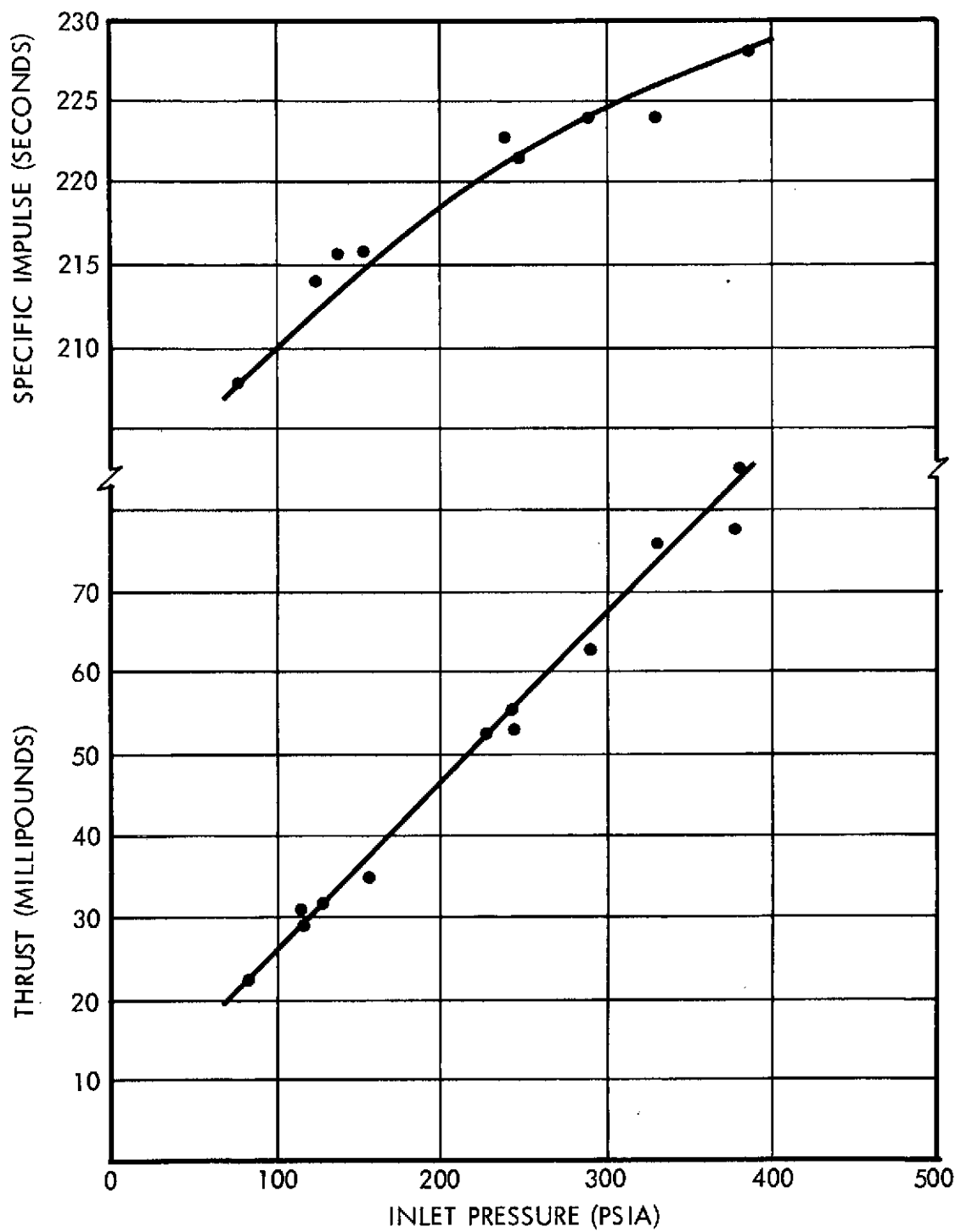


Figure 3-4. GSFC-001 Steady State Performance

The unit was proof tested at 600 psig without incident. Internal and external leakage tests at 400 psig uncovered no measurable leakage. The results of the no-flow heat loss test are presented in Figure 3-5.

The cycle life portion of the test was initiated. Most of the cycles were accumulated at 130, 250, and 375 psia inlet pressures with 25 millisecond pulses at the rate of 10 pulses per second. The chamber temperature varied between 1600 and 1710°F depending upon the inlet pressure.

Figure 3-6 contains representative chamber pressure traces at 250 psia inlet pressure with a pulse width of 25 milliseconds. In all of the photos, the time base is 20 milliseconds per centimeter and the pressure calibration is 20 psi per centimeter. It is evident from the photos that the chamber pressure decreased with pulse number during the first 100,000 cycles.

A baseline steady state test after 100,000 cycles confirmed that the chamber pressure and thrust level had degraded. The thrust level at 375 psia inlet pressure was 0.054 pound, rather than the 0.075 pound measured at the beginning of the test. The specific impulse remained unchanged. The degradation in thrust could only be the result of a flow restriction which was eventually traced to the injector. A wire was run through the injector and a sample of the propellant was withdrawn from the system for analysis. Contamination of the propellant was thought to be the cause of the flow restriction in the injector. The test was restarted. Cleaning the injector with the wire removed the flow restriction as indicated by the data contained in Figure 3-7. Steady state thrust was approximately the same as that recorded during the initial test.

During the next 1000,000 cycles, the same degradation experienced before was observed again. At 200,000 cycles the steady state thrust had degraded to 0.067 pound at an inlet pressure of 375 psia. As before, steady state specific impulse was unchanged.

Another 36,000 cycles were accumulated on the thruster before it became evident that the degradation rate was increasing. At 230,000 cycles, the peak chamber pressure at the conditions noted in Figure 3-6 was only about 50 psia. At this point the test was terminated.

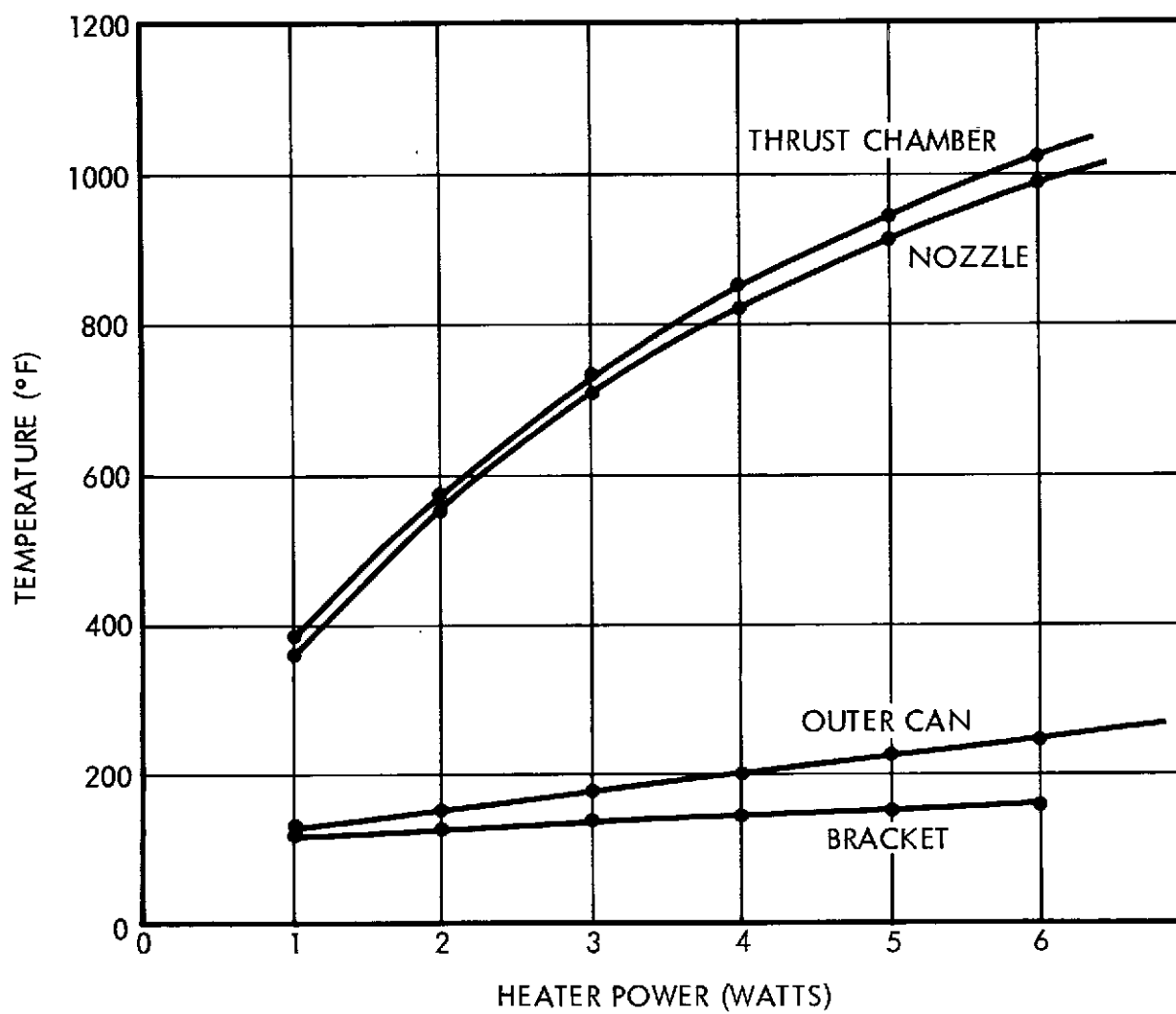
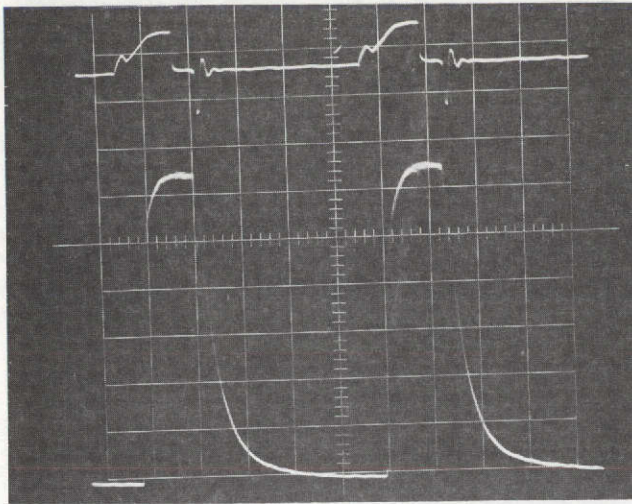


Figure 3-5. Thermal Test of GSFC-001

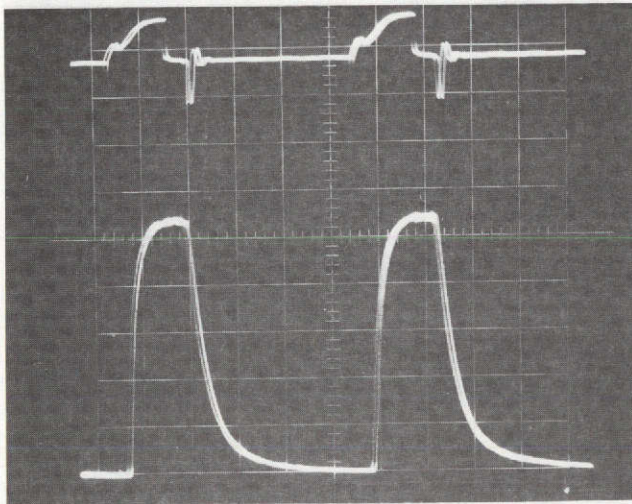


Inlet Press. = 250 psia

Scale: time = 20 ms/cm
press. = 20 psi/cm

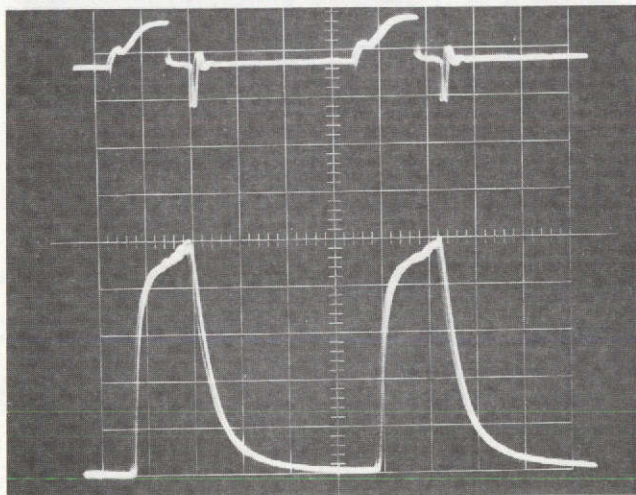
Pulses 27,570 - 27,580

$T_{ch} = 1680^{\circ}\text{F}$



Pulses 80,000 - 80,010

$T_{ch} = 1670^{\circ}\text{F}$



Pulses 100,000 - 100,010

$T_{ch} = 1640^{\circ}\text{F}$

Figure 3-6. Pulse Performance of GSFC-001

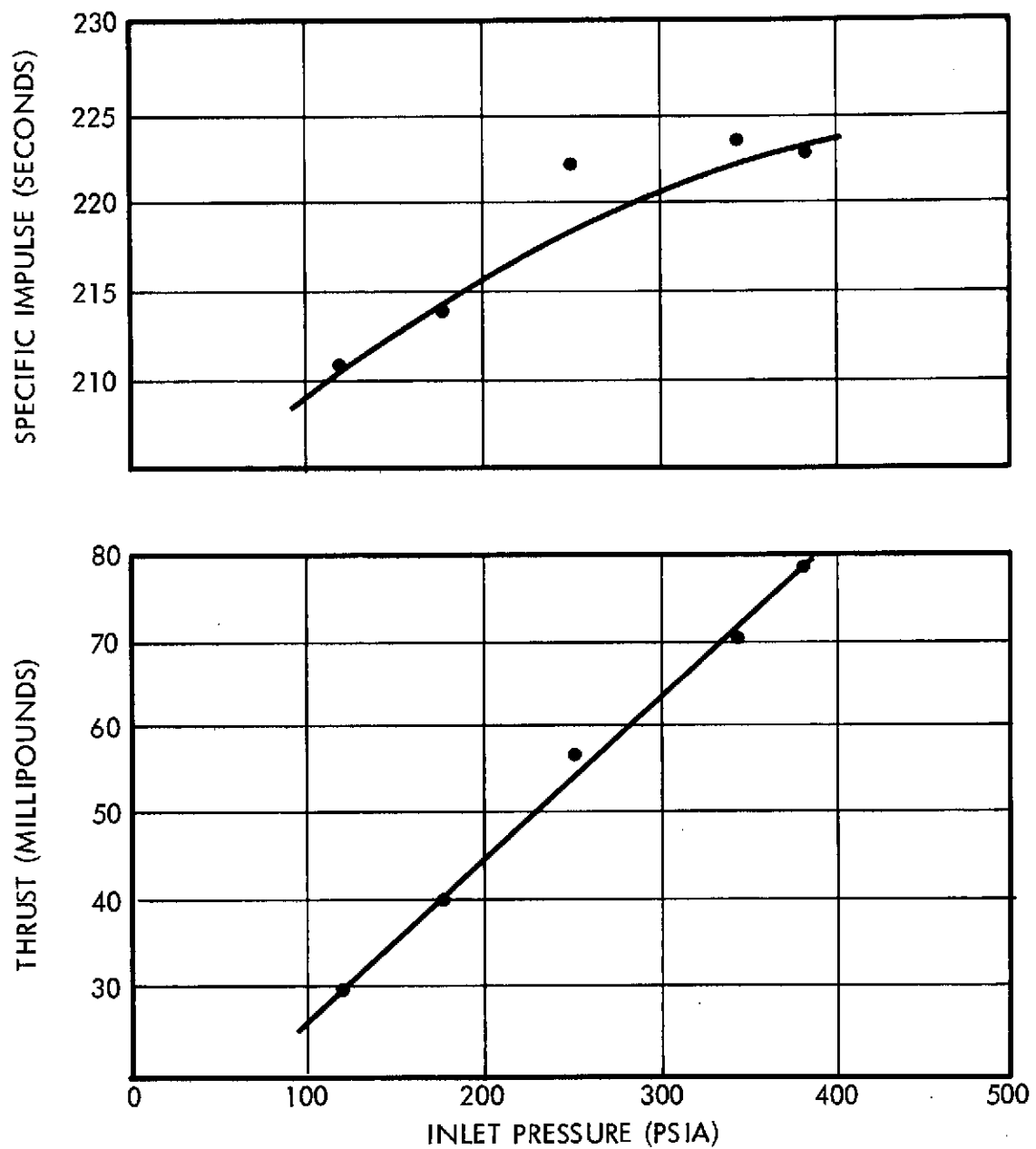


Figure 3-7. Steady State Test After 100,000 Cycles GSFC-001

The entire propellant supply system was removed from the test cell and recleaned. A fresh supply of hydrazine propellant was ordered from the Matheson Company. This propellant was returned to the vendor since it was visibly contaminated with particulate material. Forty pounds of mil-grade hydrazine was ordered from the Olin Company. This propellant was analyzed and found to meet the military specification. A portion of this propellant was loaded into the system through a 5-micron Mitex filter.

The injector was again cleaned with a wire and the test was restarted with the newly-cleaned system and clean propellant. The same degradation was again experienced and the test was terminated at 304,594 cycles.

At this time it was evident that propellant contamination was not the cause of the flow restriction. The thruster was sectioned and the injector was found to be severely nitrided. Figure 3-8 is a view of the sectioned thruster. Figure 3-9 shows the injector area. Two facts are evident from these two figures. One of the platinum screens had slipped past the retaining shoulder into the head space. This apparently had little effect on the thruster performance. Also, Inconel 600 proved too susceptible to nitriding for use as injector material. Figure 3-9 suggests that the nitrided material sloughs off the wall of the tube and is subsequently deposited downstream to form a flow restriction.

3.4.2 Evaluation of Haynes 25 Injector Material

Since Inconel 600 proved unsuitable for the injector, it was decided to test a thruster with a Haynes 25 injector. One of the "work-horse" thrusters described in Section 2.2 was reassembled and installed in the test facility. Characterization tests indicated that the thruster performance was essentially the same as that of GSFC-001.

The Haynes 25 injector was apparently only slightly more nitride resistant than the Inconel 600 injector. A significant decay in chamber pressure and thrust was experienced at about 175,000 cycles and the injector was virtually closed when the test was terminated at 193,979 cycles.

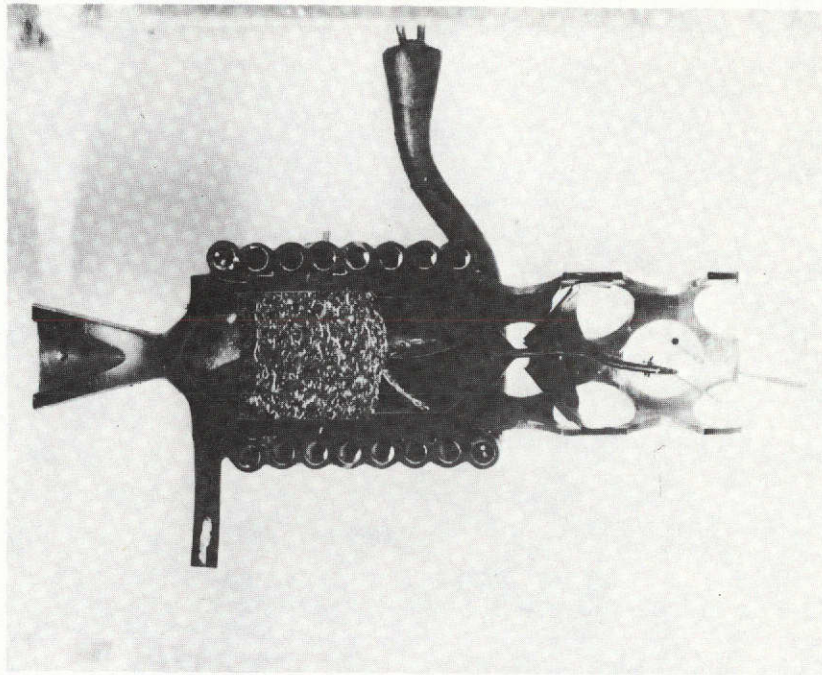


Figure 3-8. Sectional View of GSFC-001

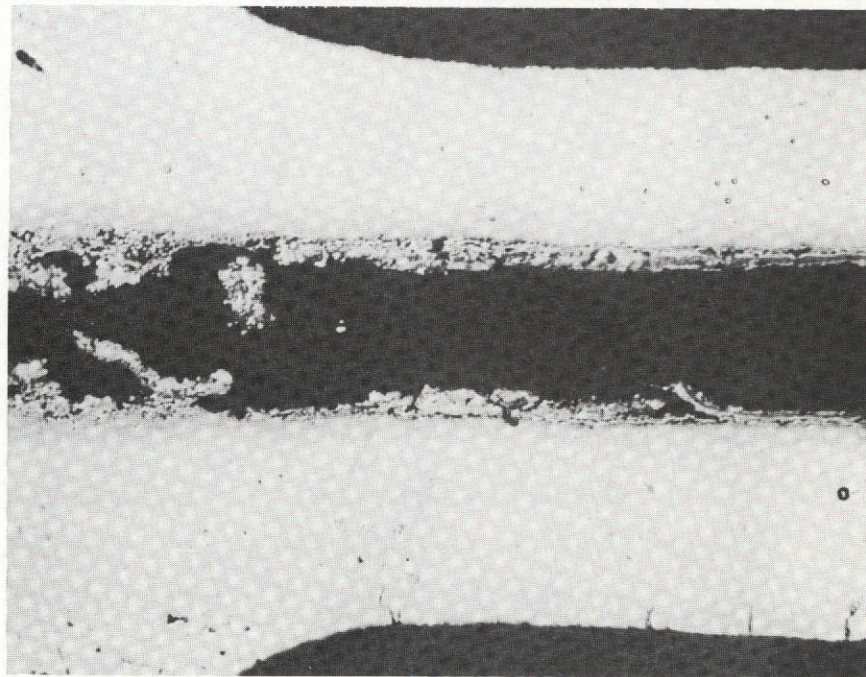


Figure 3-9. Inconel 600 Injector After 300,000 Cycles

This thruster was sectioned also. The injector tip is shown in Figure 3-10. The formation of a flow impedance occurred by the same mechanism observed with Inconel 600. Nitrided material forms on the wall, breaks off, and is carried downstream until it lodges in the tube and blocks the flow passage.

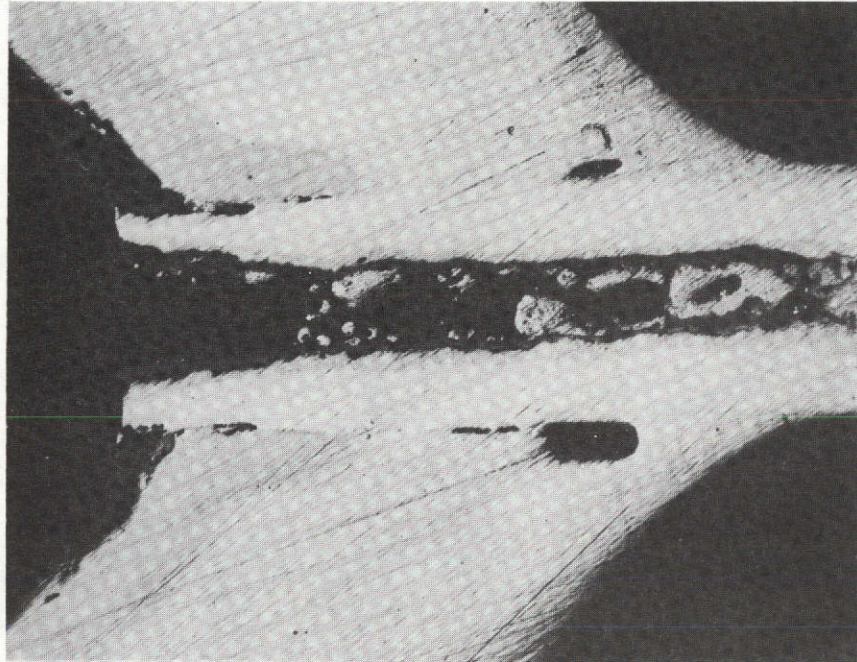


Figure 3-10. Haynes 25 Injector After 200,000 Cycles

3.4.3 Evaluation of Noble Metal Injectors

The 10^6 cycle test discussed earlier in Section 3.1 was conducted on a development thruster which used a platinum-10 percent iridium injector. There was no evidence of injector nitriding in this thruster after the test. For this reason, it was decided to fabricate an Engineering Model thruster with a platinum tube even though the pulsing characteristics with platinum had been found earlier to be somewhat inferior to those with either Haynes 26 or Inconel injectors. The use of platinum seemed to increase the tendency to vaporize in the injector.

Thruster GSFC-002 was fabricated with a platinum-10 percent iridium injector brazed to the Haynes 25 chamber with a palladium-cobalt braze alloy. A photo of this braze joint is shown in Figure 2-15. Character-

ization tests were conducted and the cycle life test was initiated. Figure 3-11 is a trace of a 0.087 second pulse with a cycle rate of 2 pulses per second. The chamber temperature was 1620°F. At 3,681 pulses, a sudden decrease in the peak chamber pressure was observed and the test terminated. The cause of the pressure decrease was a hairline crack in the braze area between the injector and the chamber.

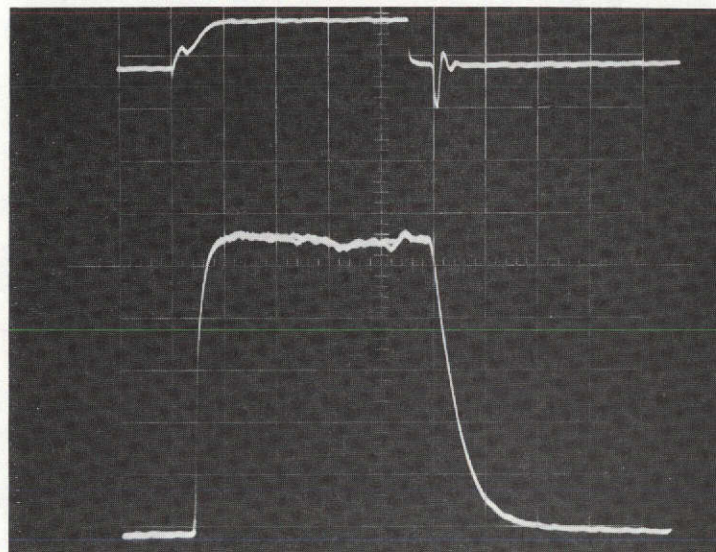


Figure 3-11. GSFC-002 Pulse Shape

Thruster GSFC-003 was fabricated using the same techniques as GSFC-002. Particular care was taken to produce an acceptable braze fillet between the injector and the head end. The result was the rather bulbous fillet shown in Figure 3-12. The thruster assembly was completed and a cycle life test was initiated. The test was terminated at 127,164 pulses because the peak chamber pressure had decreased to about 80 percent of its initial value. A crack in the injector tube was noted just upstream of the braze fillet. Figure 3-13 shows the sectioned thruster. (Note that the heater is wound in two layers. GSFC-003 was the first of the EM thrusters to use a heater designed to produce 5 watts at 28 vdc. All of the preceding thrusters used lower voltage, shorter heaters.)

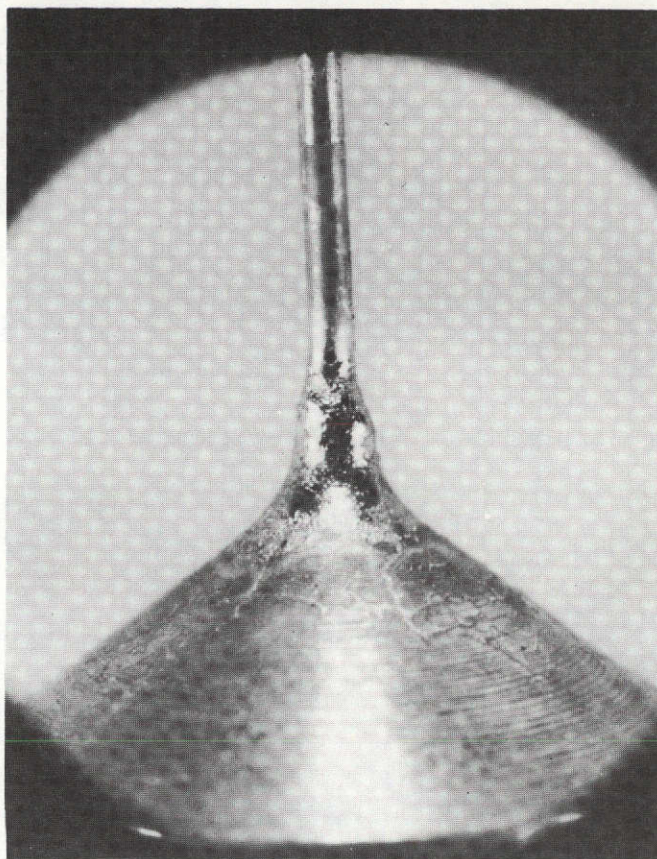


Figure 3-12. GSFC-003 Braze Fillet Prior to Final Assembly

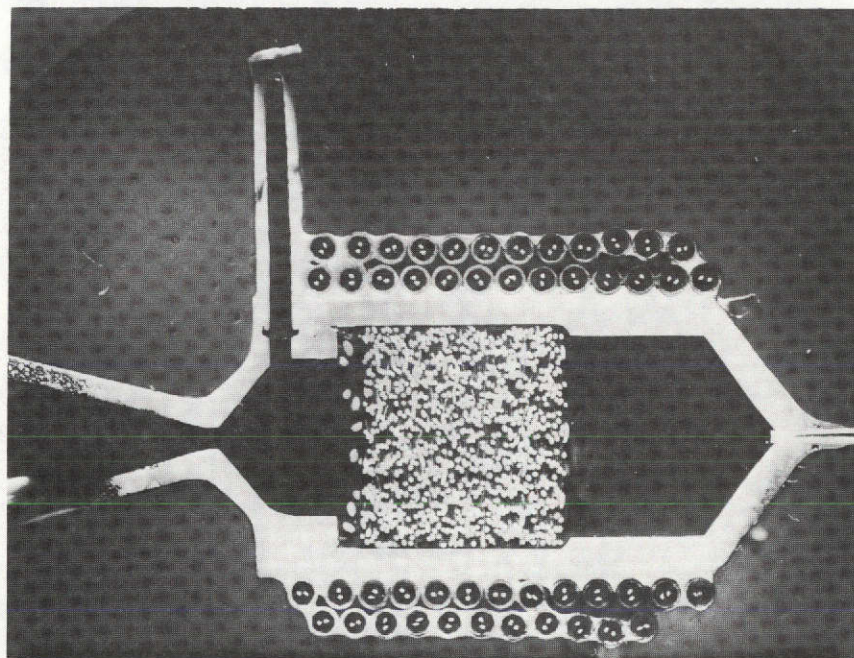


Figure 3-13. Thruster GSFC-E003

Figure 3-14 shows the injector in the area of the braze fillet. (Note: During the polishing process, injector material was pulled out at several locations.) It is evident that the injector material was severely attacked at the grain boundaries. Material analyses performed at GSFC and TRW revealed the presence of silicon and silicon-based alloys contaminating the injector grain boundaries.

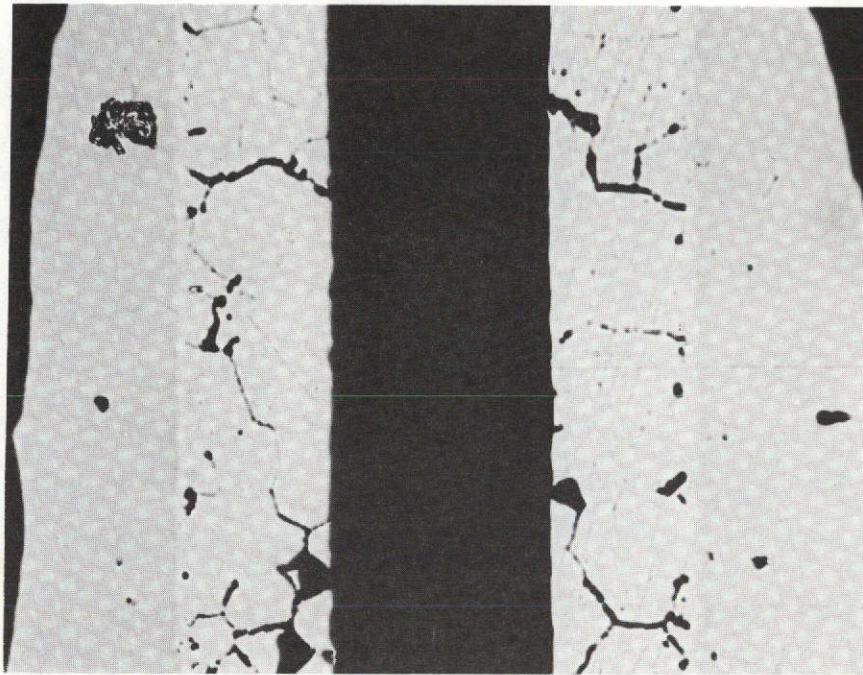


Figure 3-14. Pt-10 Ir Injector

At this point in the program a rather lengthy and ultimately unsuccessful braze development program was initiated to establish a method of attaching the platinum-iridium injector to the Haynes 25 chamber. Several braze alloys were evaluated as well as a number of different braze cycles and environments. The braze development program eventually achieved joints that were virtually free of silicon contaminants. However, the program was unsuccessful in eliminating Haynes 25 thruster body material constituents (primarily manganese and chromium which had vapor deposited on the braze alloy and injector surfaces) from contaminating the injector grain boundaries.

A detailed stress analysis indicated that the thermal relief bend in the injector was inadequate. The design was modified to include a complete loop in the injector.

One example of the braze development tests is shown in Figures 3-15, 3-16, and 3-17. Two injector/chamber assemblies were brazed simultaneously. One of the units, together with a sample of tubing which had seen the same braze cycle, was subjected to the ductility test shown in Figure 3-15. The joint was then sectioned as shown in Figure 3-16. This test indicated that the joint was sound and the grain structure appeared typical of the platinum-iridium material. However, when the second chamber was built up into a complete thruster, the injector failed (Figure 3-17) — apparently due to the seemingly negligible contaminants in the grain boundaries.

The logical next step would have been to change chamber materials, perhaps to a noble metal. This change would simplify the braze problem or perhaps allow it to be circumvented altogether by using an electron beam weld joint. Unfortunately the program resources and schedule did not allow this option.

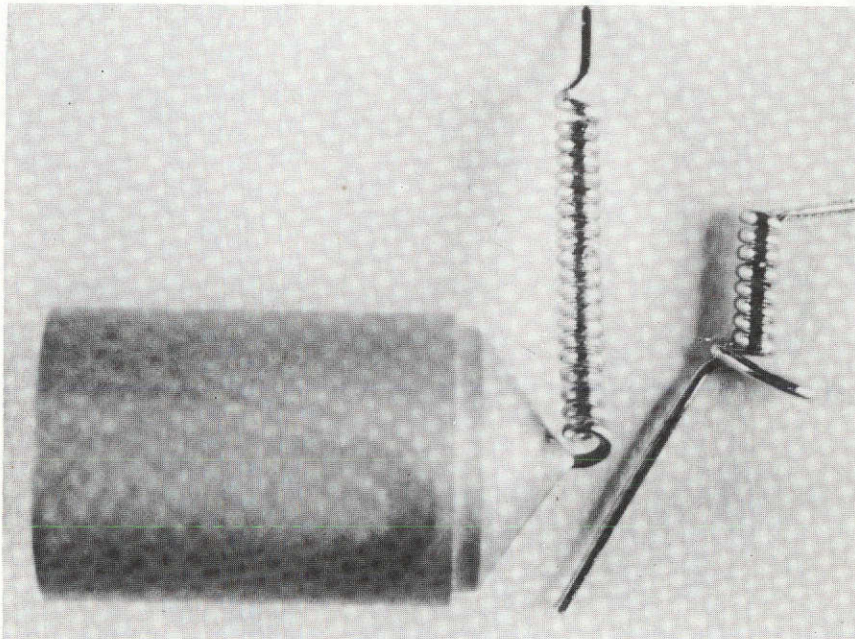


Figure 3-15. Injector Ductility Test

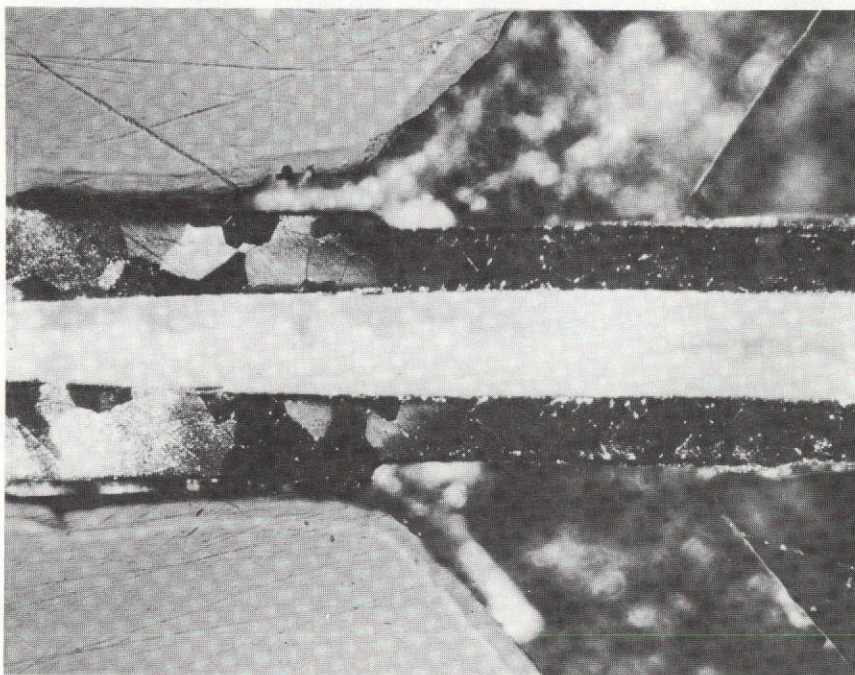


Figure 3-16. Platinum Structure with Polarized Light

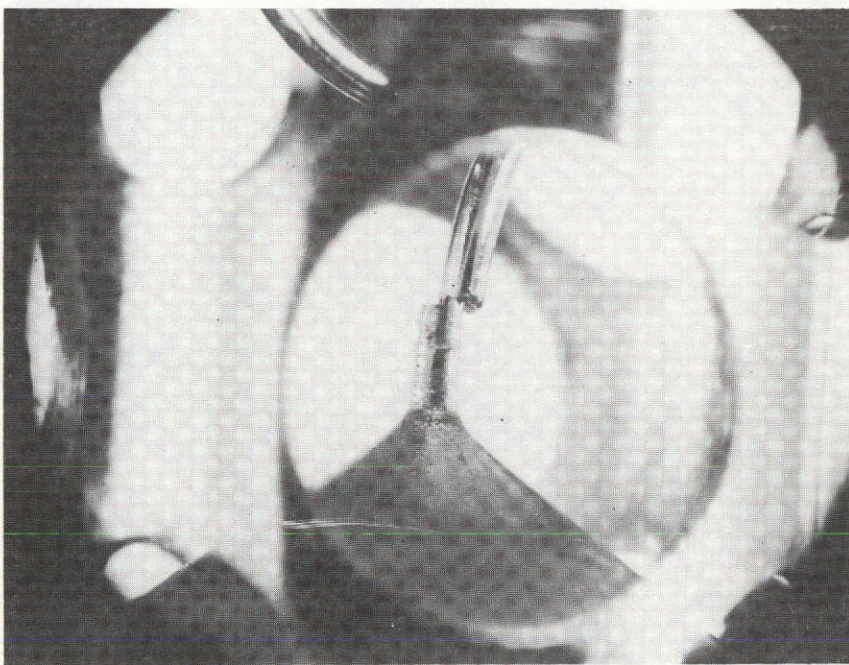


Figure 3-17. Failed Injector After Final Braze

4. ENGINEERING MODEL TESTS

Thruster GSFC-004 successfully met the requirements for 300,000 pulses and 30 hours of steady state operation. At the conclusion of the test, the thruster was still operable and produced steady state specific impulse values well in excess of 200 seconds. Pulse characteristics remained essentially unchanged. The injector nitriding problem discussed in Section 3 was still evident, however, and resulted in a gradual decrease in thrust level throughout the test. It is estimated that the total throughput of GSFC-004 was 36 pounds of anhydrous hydrazine.

As stated previously in Section 3.4, the life cycle pulse rate was greatly reduced to minimize the nitriding rate of the Haynes 25 injector material and to reflect a more mission-representative duty cycle. The life cycle test was performed predominantly at 2 pulses per second with a 25 millisecond command pulse width.

4.1 Thruster Description

The thruster designated GSFC-004 was essentially identical to that shown earlier in Figures 2-9 and 2-10. The primary exception was that the injector tube incorporated a full loop rather than a simple bend to accommodate the thermal stresses. Incorporation of the loop increased the overall injector length 0.55 inch to about 1.75 inch. The injector was made from Haynes 25 tubing with an inside diameter of about 0.006 inch and an outside diameter of 0.014 inch. The use of Haynes 25 represented a technical compromise since earlier tests had indicated that a significant amount of nitriding was very likely. EHT GSFC-004 used a heater with a resistance of 146 ohms, which produced 5 watts at 27 vdc.

4.2 Test Methods

All of the tests were conducted in a horizontal, cylindrical vacuum chamber that is four feet in diameter and four feet long. The chamber is evacuated by two 10-inch diffusion pumps and an 80-cfm rotary mechanical pump. Thermal and pulse-mode performance tests were conducted under high vacuum (10^{-5} to 10^{-4} torr) conditions. Steady state performance measurements were conducted with only the mechanical pump.

Figure 4-1 shows the instrumented EHT mounted on the thrust balance. Figure 4-2 shows the overall installation including the flow measurement device which is a nitrogen-pressurized piston that displaces propellant stored within a small-diameter cylinder. Figure 4-3 shows the data acquisition system. Operating and performance parameters for pulsed or steady state operation may either be recorded on an oscillograph or magnetic tape. The oscillograph data were reduced by hand in a conventional manner. A sample is included in Figure 4-4. Data acquired on magnetic tape was reduced by the computer in the left hand portion of Figure 4-3 and printed out in engineering units.

4.3 Test Description and Results

The tests conducted on the Engineering Model EHT (GSFC-004) included a number of preliminary tests, a cycle life test, and a steady-state life test. In addition, a number of "baseline" tests were interspersed throughout the life tests to check the thruster performance. The total test program for GSFC-004 lasted about two months.

The preliminary tests included a physical examination, internal and external leakage, proof pressure, and a no-flow thermal test. The results of the thermal test are given in Figure 4-5. With a holding power of 5 watts, the thruster reached a chamber temperature of 1100°F. The temperatures at several other locations are also noted. It should be pointed out that the thruster temperature distribution changes significantly during periods of propellant flow. The chamber heats up to 1600-1700°F under steady state conditions because of the chemical energy input. The valve and bracket decrease slightly in temperature because of the cooling effect of the propellant.

The preliminary tests also included a pulse-mode test amounting to about 5000 cycles. During this "run-in" test, the shape of the chamber pressure pulse stabilizes and the steady state chamber pressure roughness decreases from the initial value. This improvement in thruster characteristics during initial operation is attributed to an unidentified modification of the screen pack surface characteristics.

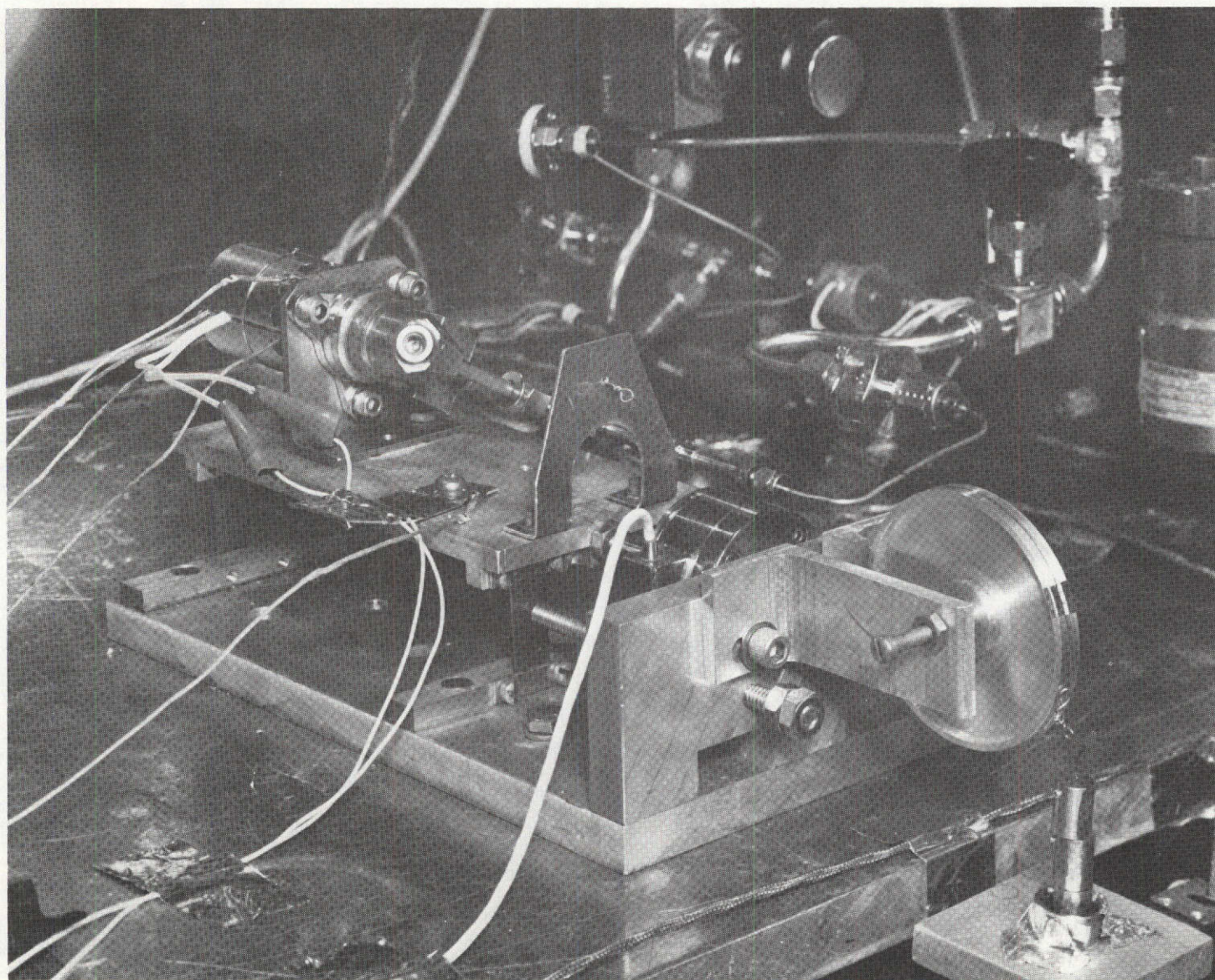


Figure 4-1. EHT Mounted on Thrust Stand

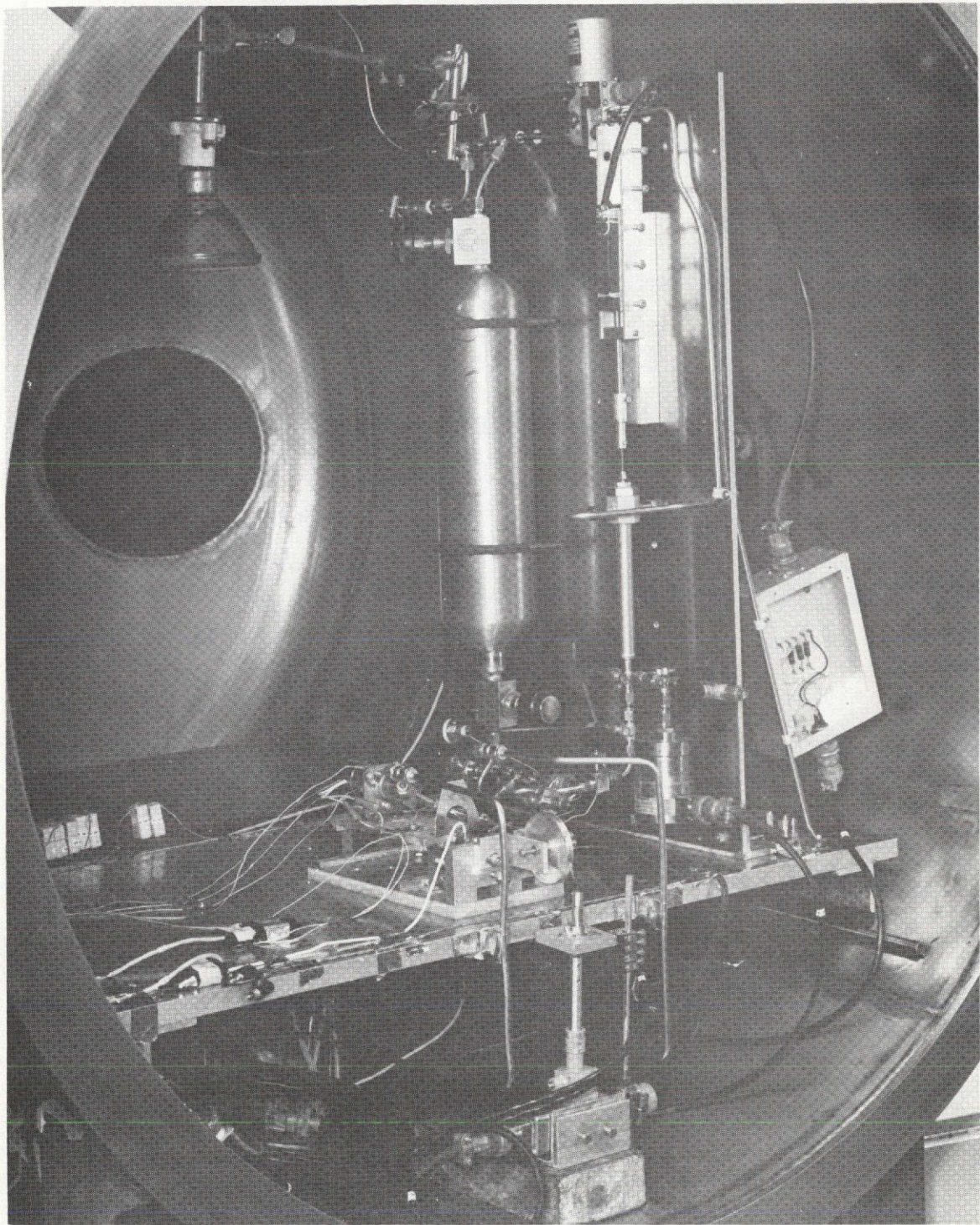


Figure 4-2. EHT Test Setup

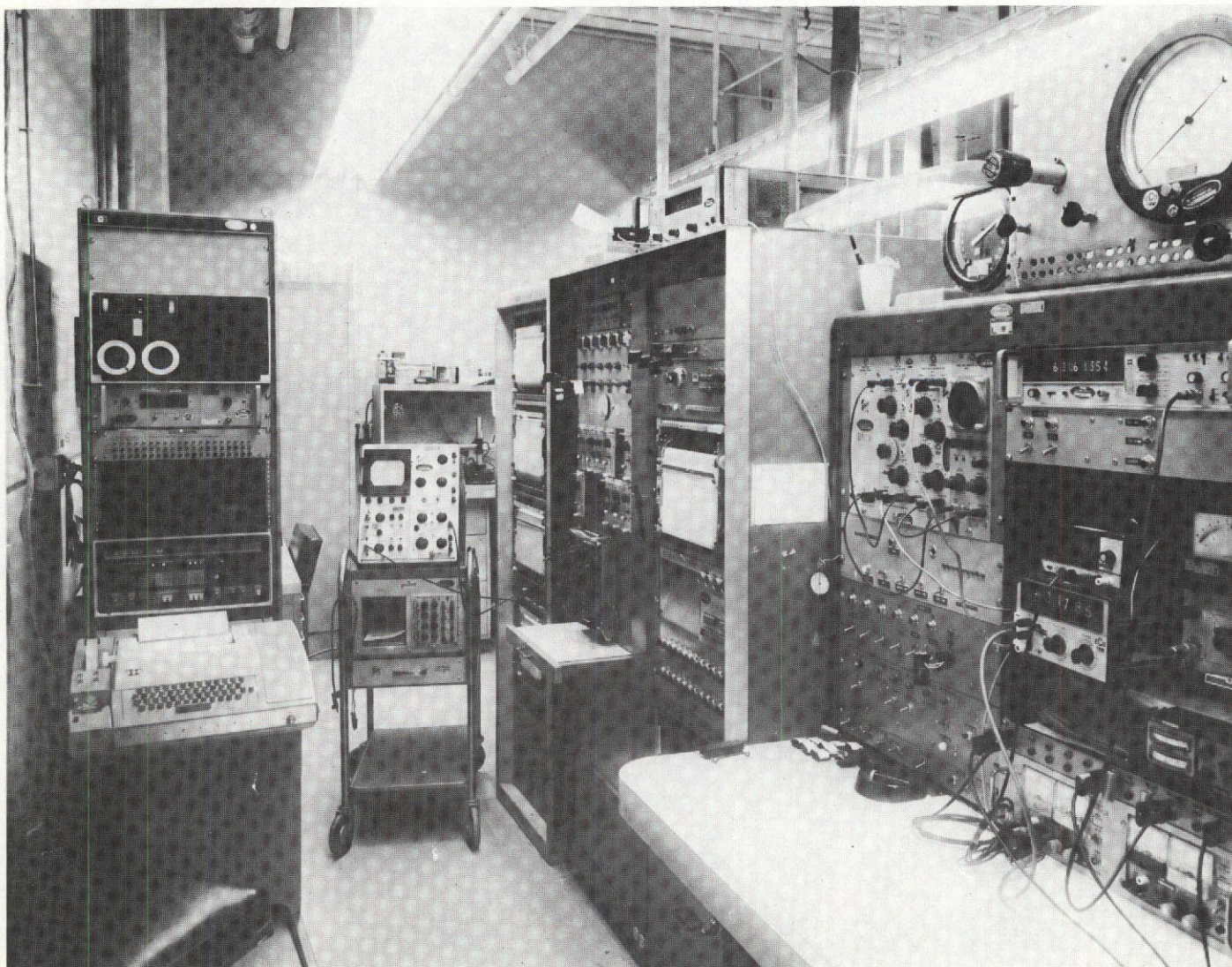


Figure 4-3. Data Acquisition System

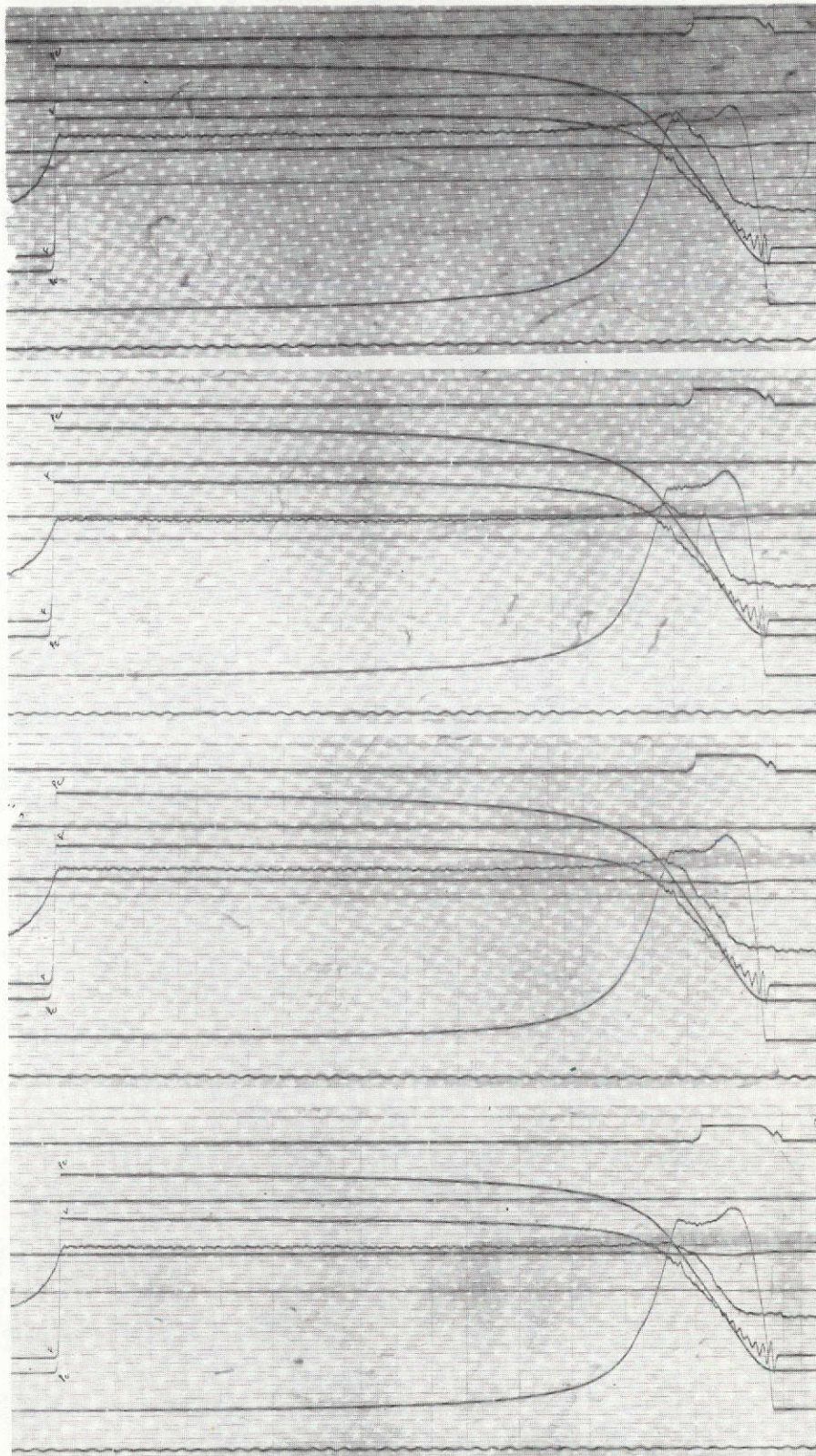


Figure 4-4. Sample of Analog Data

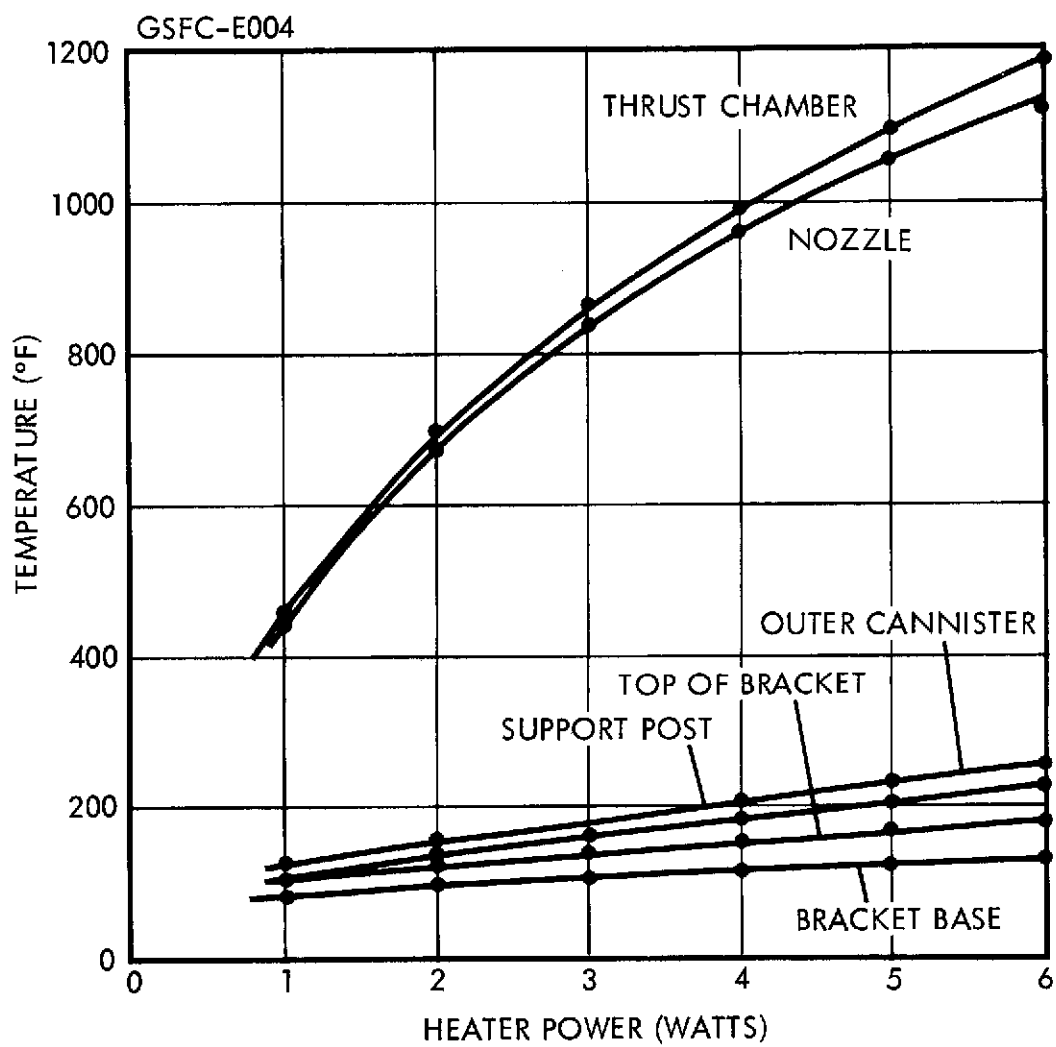


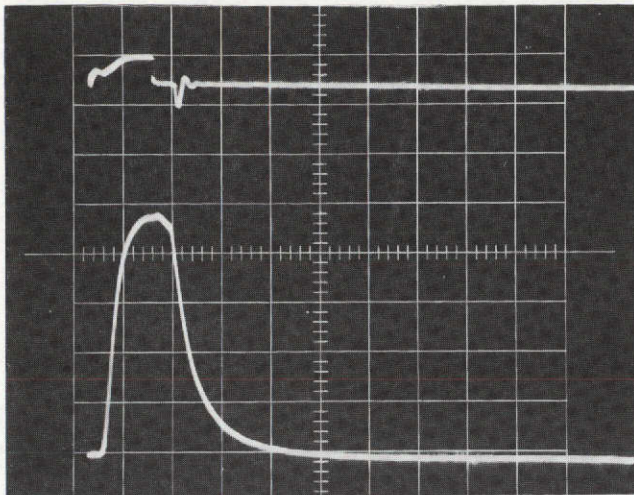
Figure 4-5. GSFC-004 Thermal Test

The cycle life test was conducted at inlet pressures of 135, 250 and 375 psia. Pulse width was varied from 0.025 to 0.200 second and the repetition rate was varied from one pulse every 10 seconds to 4 pulses per second. The majority of the cycles were accumulated with a command pulse width of 0.025 second and a repetition rate of 2 cycles per second. Figure 4-6 shows the chamber pressure traces at representative times during the 300,000 cycle test. In all cases, the inlet pressure is 250 psia, the command pulse width is 0.025 second, the vertical scale is 20 psia/cm and the time base is 20 msec/cm. The test was terminated at 315,751 cycles.

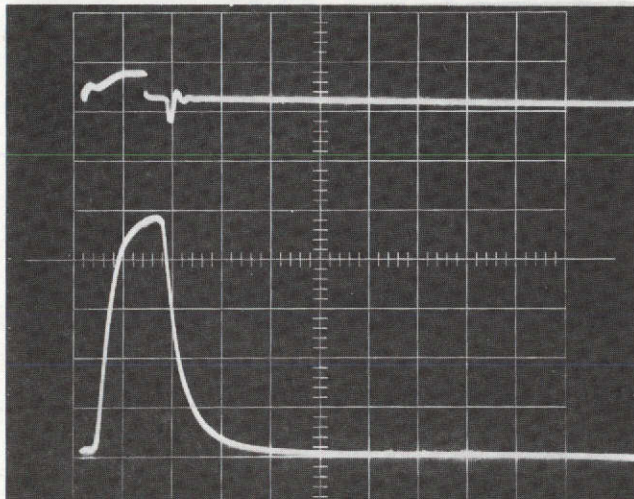
Figure 4-7 indicates the peak chamber pressure at 250 psia inlet pressure for 0.025 second pulses as a function of the number of cycles. At the beginning of the test, the maximum pressure was about 105 psia. The peak pressure degraded to about 90 psia over the first 100,000 cycles and was nearly stable for the remainder of the cycle life test.

The impulse delivered by the thruster is a function of the inlet pressure and the pulse width as shown in Figure 4-8. These data were obtained at the end of the steady state life test. Each point plotted in Figure 4-8 represents a train of about 50 pulses. At each operating condition, the impulse bit variability amounted to less than five percent. At a pulse width of 50 milliseconds, the impulse bit varies from about 0.6 to 1.4 millipound-second.

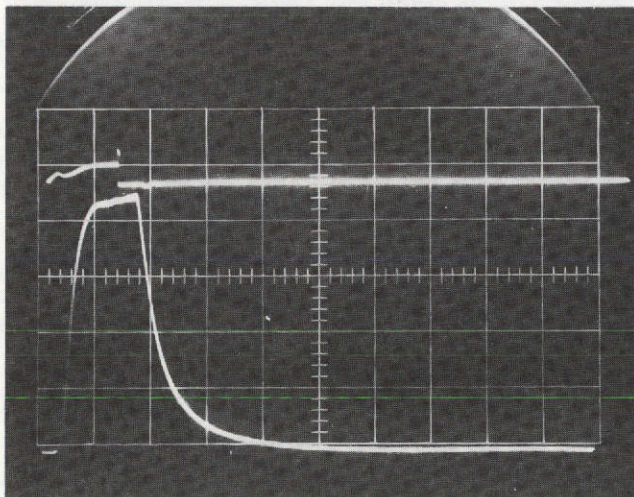
Figure 4-9 includes representative specific impulse data taken after the Engineering Model test. The thruster was GSFC-005, a deliverable unit. As indicated, the delivered specific impulse is sensitive to the command pulse width. For pulses with a 0.050 second duration, the specific impulse is about 160 seconds. The low delivered specific impulse is the result of dribble volume effects and inefficiencies associated with the nozzle expansion process. Examination of Figure 4-6 indicates that much of the impulse provided by a short pulse is delivered under transient conditions wherein the chamber pressure is either increasing or decreasing. Under these reduced flow conditions, viscous losses in the nozzle becomes significant. The dribble volume effect is also the result of inefficient expansion. Liquid hydrazine is "stored" in dribble volume cavities down-



Pulse No.
22,331 to 22,341

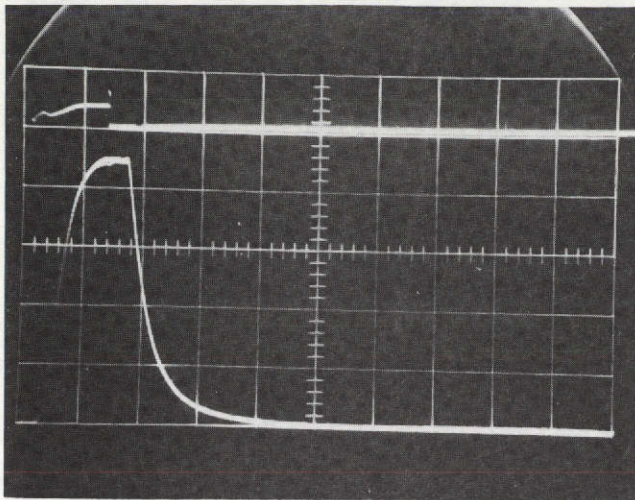


Pulse No.
58,001 to 58,021

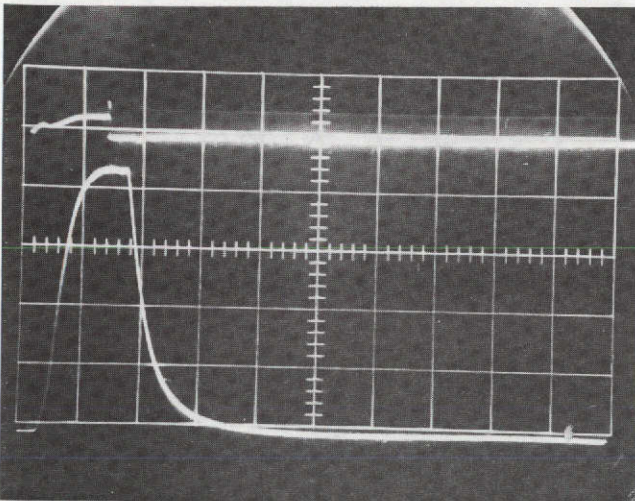


Pulse No.
103,500 to 103,510

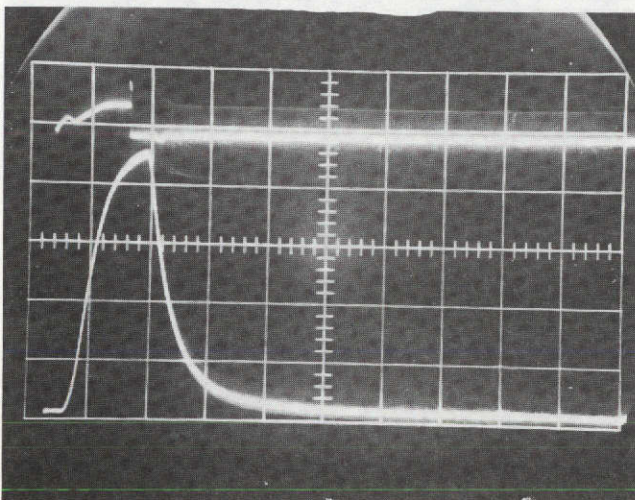
Figure 4-6. Cycle Life Test Data



Pulse No.
156,109 to 156,119



Pulse No.
200,240 to 200,250



Pulse No.
314,530 to 314,540

Figure 4-6. Cycle Life Test Data (Continued)

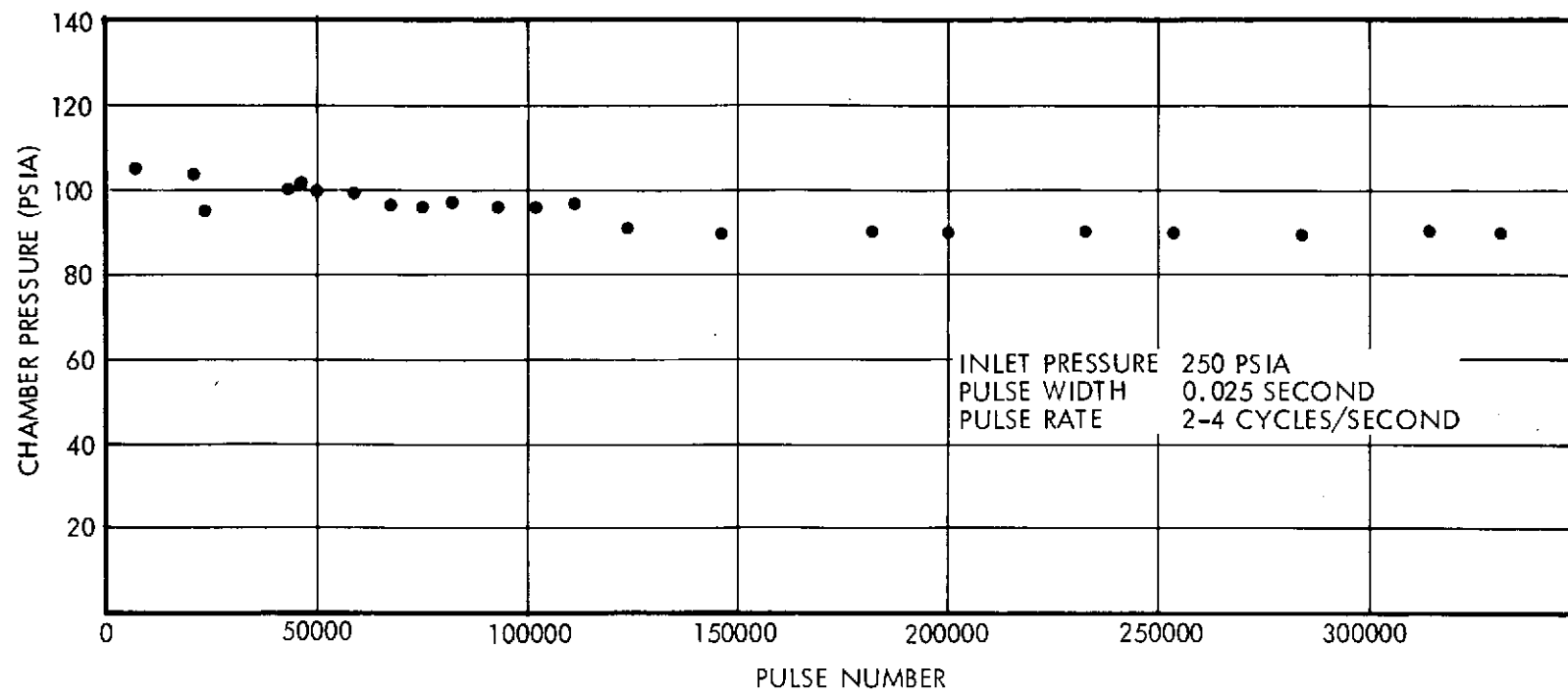


Figure 4-7. Peak Chamber Pressure versus Cycle Life

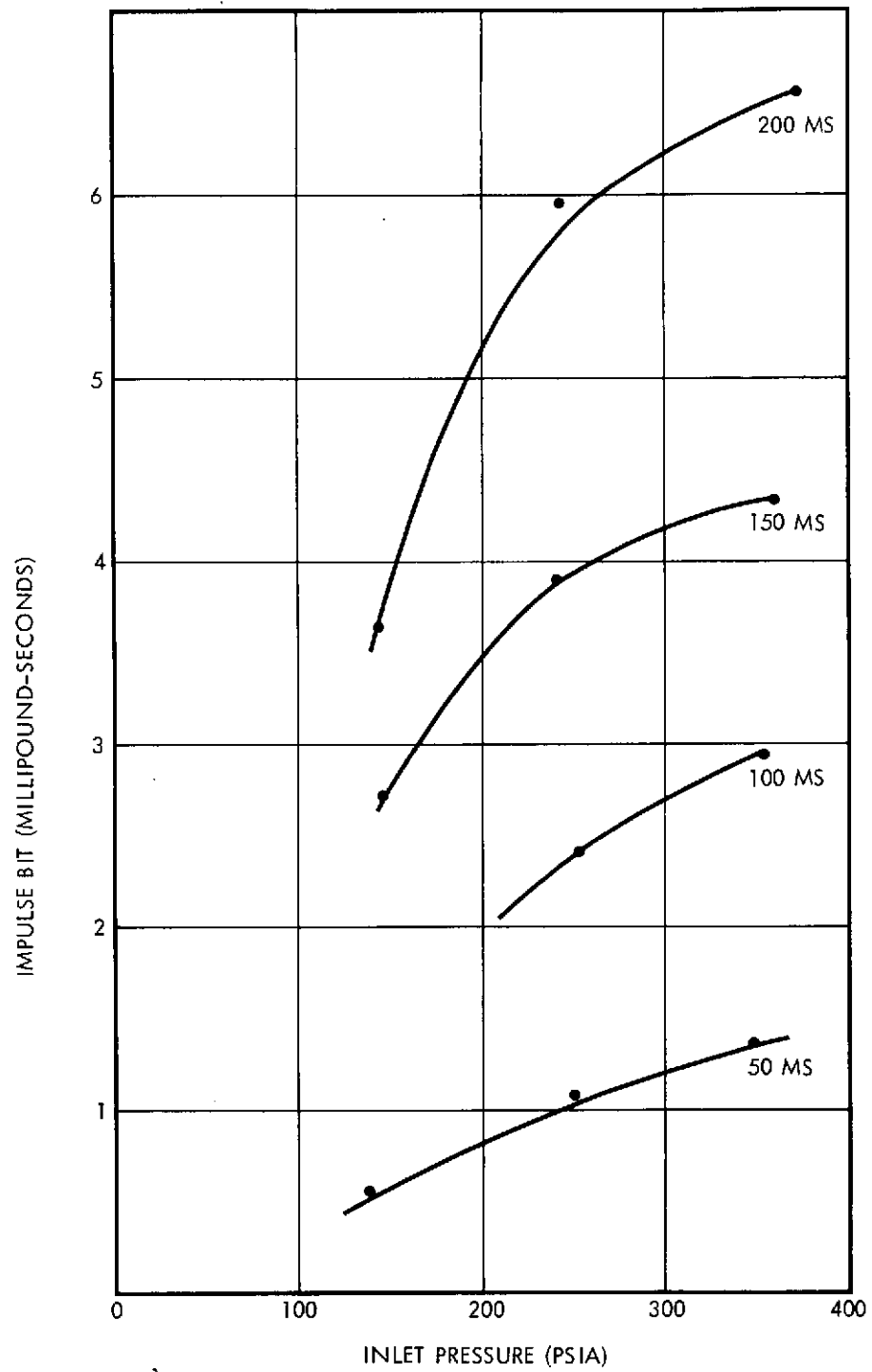


Figure 4-8. Delivered Impulse Bit

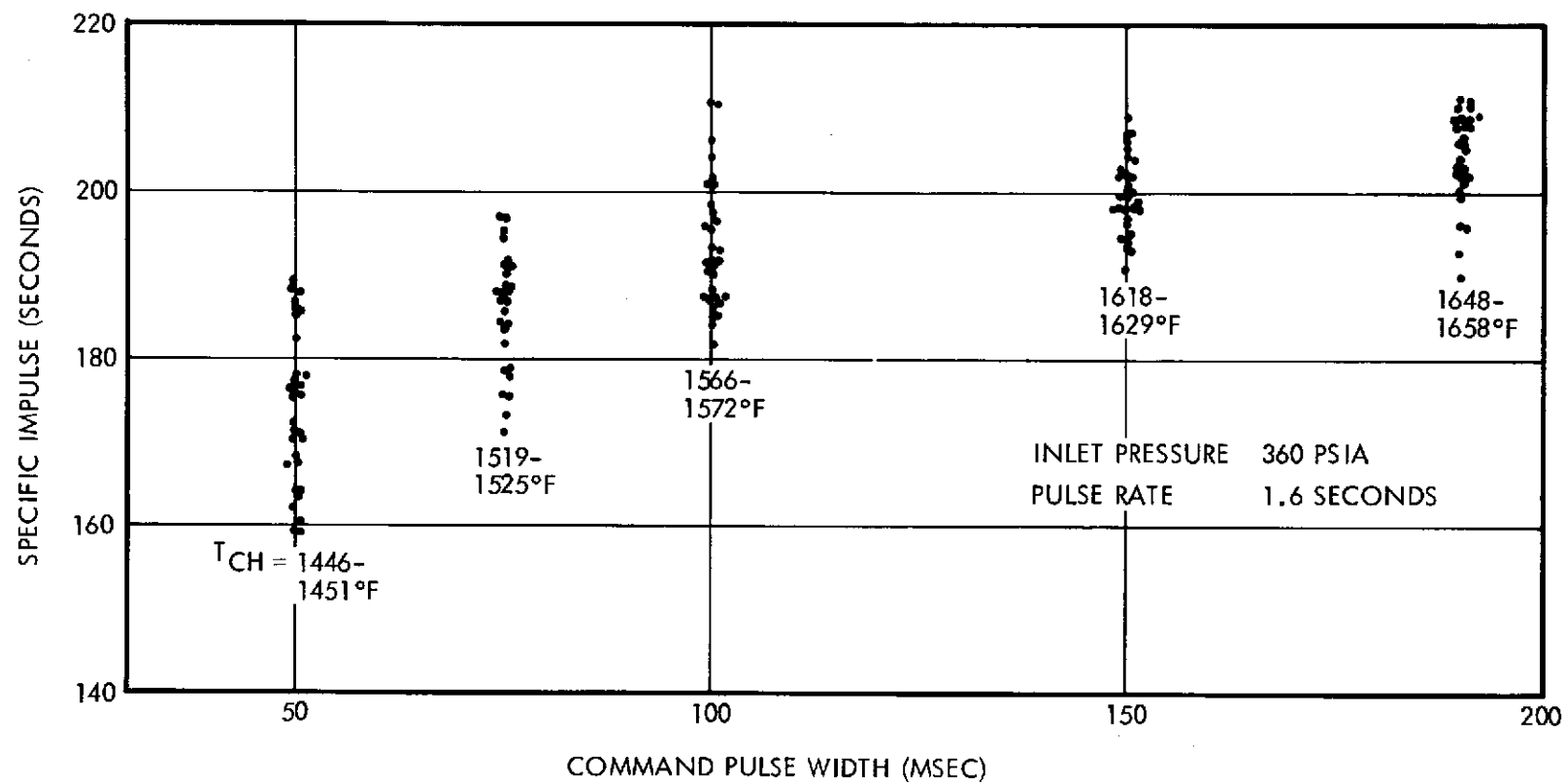


Figure 4-9. Specific Impulse Data

stream of the valve seal and in the injector upon valve closure. Once the feed system driving pressure is lost, this liquid is expelled quite slowly and inefficiently with a very low chamber pressure.

For pulse widths longer than 0.050 second, the transient effects become less significant and the performance is improved. At pulse widths of 0.10 second and longer, the specific impulse is greater than 180 seconds. At pulse widths of 0.20 seconds and longer, the performance approaches the steady state value. Data from this test sequence is given in Appendix A. The data is useful not only for observing the characteristics of the thruster, but also for demonstrating the capability of the computerized data acquisition system.

The steady state portion of the life test was initiated immediately following the cycle life test. No changes were made to either the thruster or the test equipment. The test was not continuous; periodic shut-downs for refueling were required since the test tank shown in Figure 4-2 has a capacity of only 5 pounds of hydrazine.

Figure 4-10 is a plot of the test history. With the exception of about 1.5 hours, the entire test was conducted at the inlet pressure levels of 135, 250, and 375 psia. Between the twentieth and twenty-fourth hour, the pressure was gradually decreased from 375 to 125 psia to simulate a blowdown situation.

Figure 4-11 shows the chamber pressure traces at representative times during the test. The letter notations in Figure 4-11 correspond to those in Figure 4-10. Several observations can be made from the figure. At pressure levels of 135 and 250 psia, the chamber pressure roughness amounted to only one or two percent at the beginning of the test. Roughness at 375 psia was about ± 4 percent. At the end of the test the roughness at 250 psia had increased to about ± 5 percent. Also, the chamber pressure degraded throughout the steady state life test. Over the thirty-hour period, the chamber pressure at 250 psia inlet pressure degraded from about 100 psia to about 75 psia. This is believed to be the result of a nitride layer in the injector tube.

The temperature distribution of the thruster during steady state firing is indicated in Figure 4-12. These data were taken during the twentieth hour of the steady state test with an inlet pressure of 250 psia.

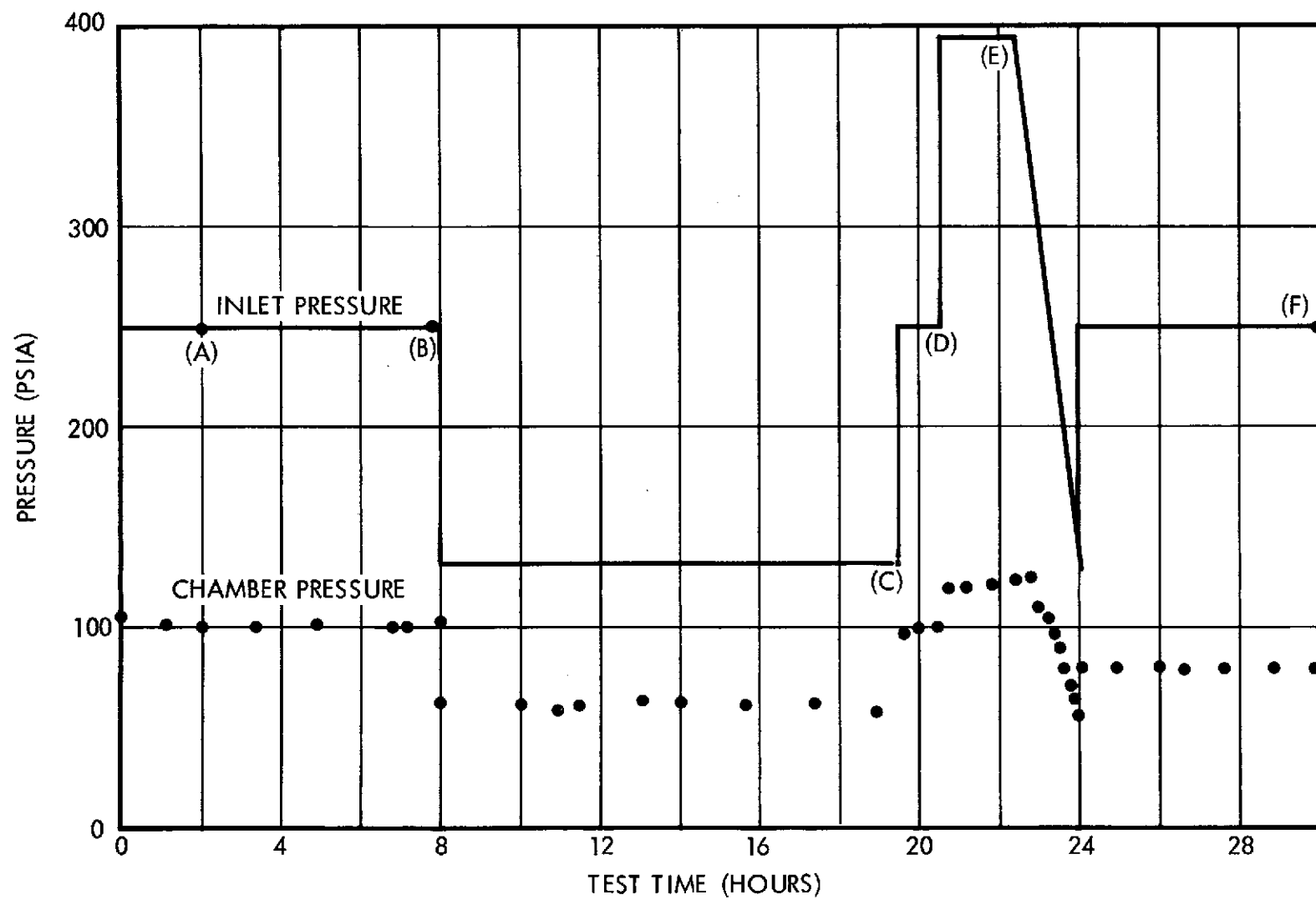
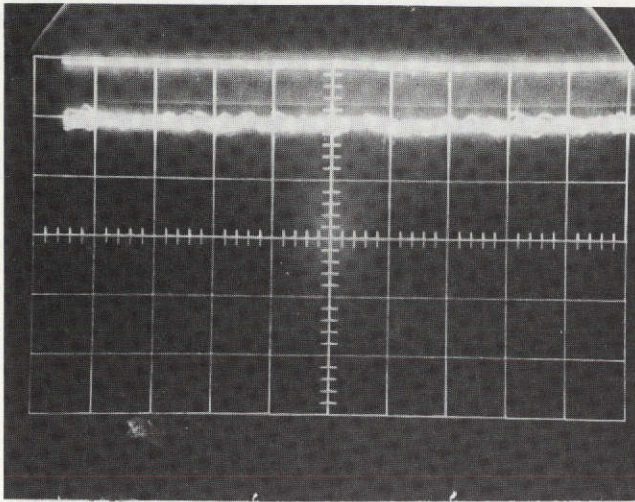
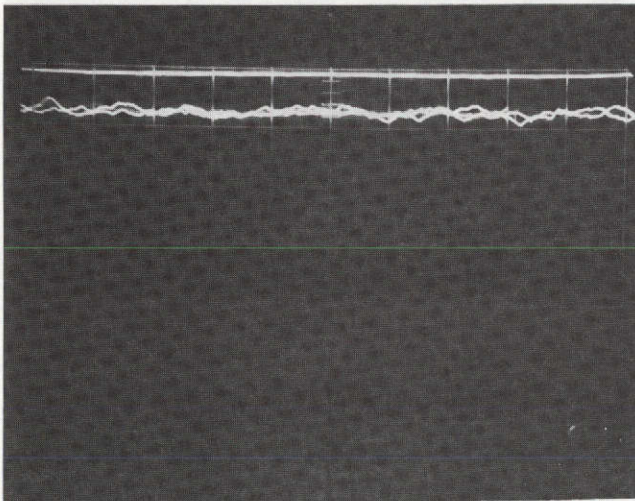


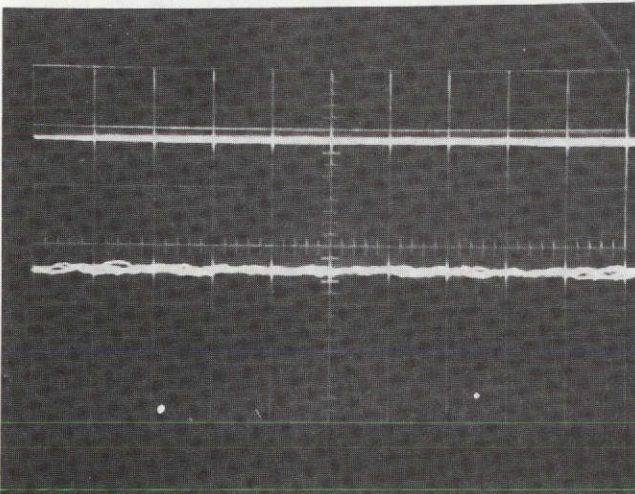
Figure 4-10. Steady State Test History



(A) $P_{in} = 250$ psia
 $T_{ch} = 1680^{\circ}\text{F}$
 $P_c = 100$ psia

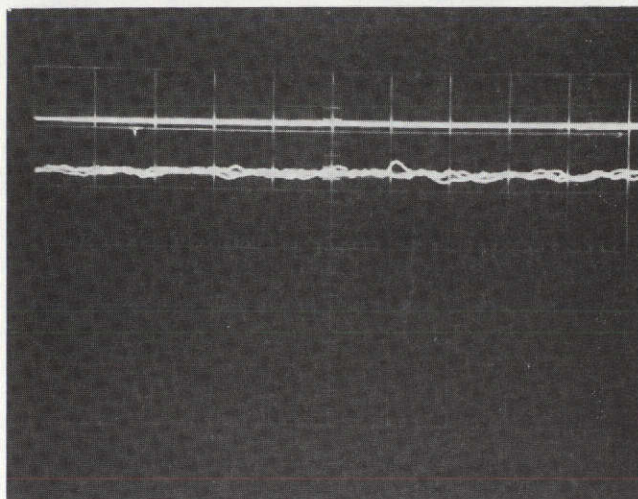


(B) $P_{in} = 254$ psia
 $T_{ch} = 1690^{\circ}\text{F}$
 $P_c = 105$ psia

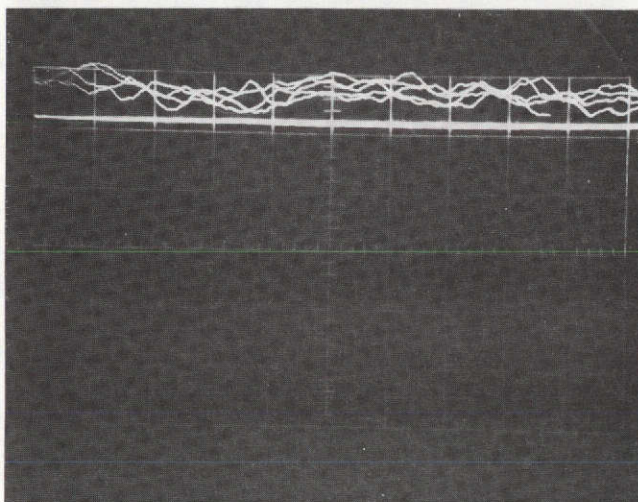


(C) $P_{in} = 136$ psia
 $T_{ch} = 1630^{\circ}\text{F}$
 $P_c = 56$ psia

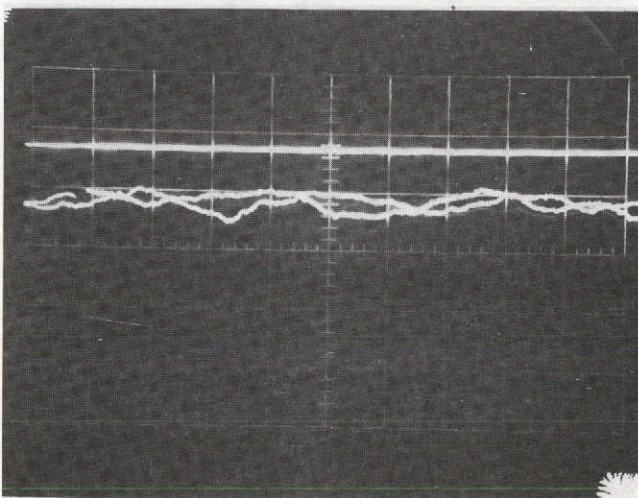
Figure 4-11. Steady State Life Test Data



(D) $P_{in} = 254 \text{ psia}$
 $T_{ch} = 1670^{\circ}\text{F}$
 $P_c = 85 \text{ psia}$



(E) $P_{in} = 378 \text{ psia}$
 $T_{ch} = 1680^{\circ}\text{F}$
 $P_c = 115 \text{ psia}$



(F) $P_{in} = 250 \text{ psia}$
 $T_{ch} = 1620^{\circ}\text{F}$
 $P_c = 75 \text{ psia}$

Figure 4-11. Steady State Life Test Data (Continued)

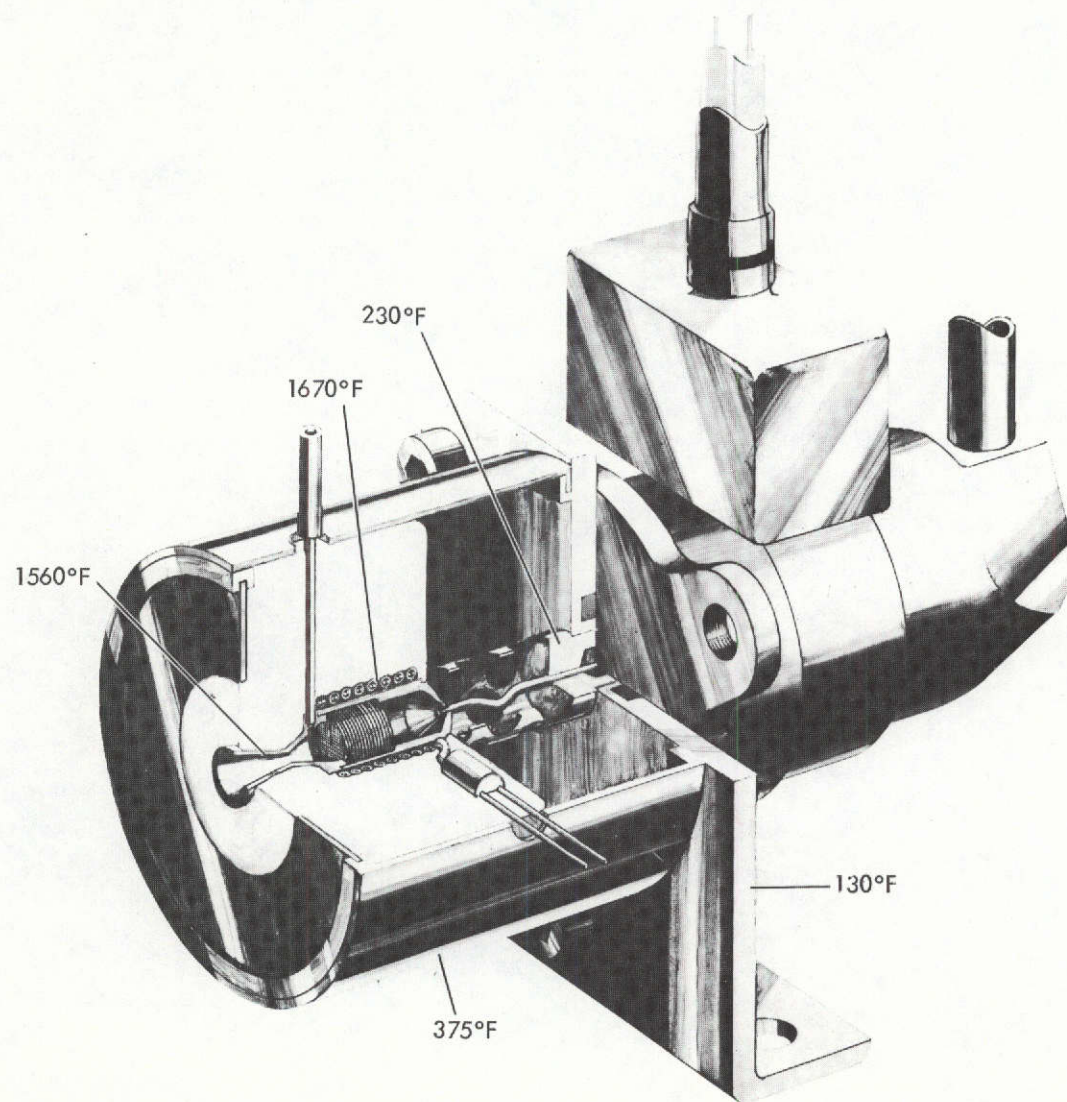


Figure 4-12. Steady State Temperature

Figure 4-13 summarizes the steady state performance of GSFC-004. The data with the circular symbols were obtained prior to the cycle life test; the data represented by the square symbols were taken following the steady state test. Steady state thrust degraded by about 35 percent. Steady state specific impulse remained above 200 seconds over the entire inlet pressure range for the duration of the test.

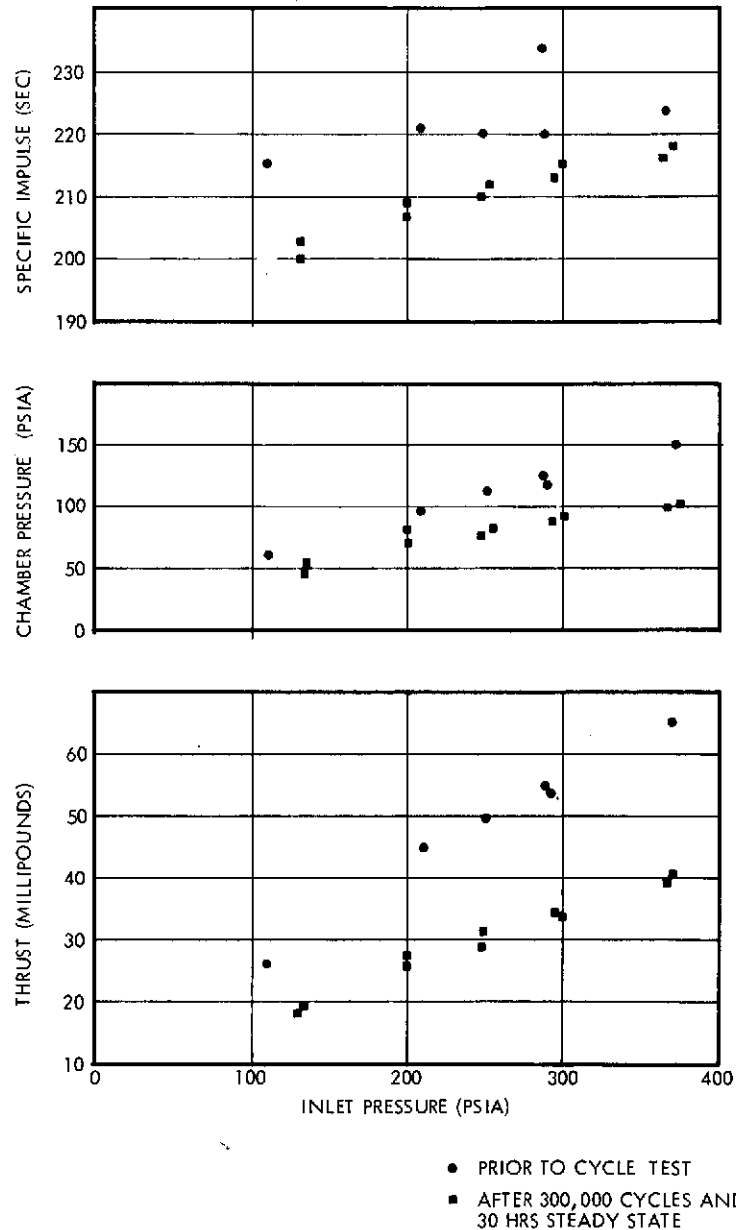


Figure 4-13. Steady State Performance Summary

5. CONCLUSIONS

The results of the preliminary tests and the Engineering Model tests indicate that small thermal-decomposition hydrazine thrusters are capable of rapid flight-qualification for spacecraft attitude- and orbit-control applications. The Engineering Model life test included 300,000 cycles and 30 hours of steady state operation on a single thruster. This demonstrated life capability appears adequate for several planned missions. Specific conclusions can be drawn from the Engineering Model Fabrication and Test Task:

- o The general design of the EHT is adequate for flight qualification in terms of thermal, mechanical, and electrical interfaces.
- o The steady state specific impulse of the thruster exceeded 200 seconds throughout the entire life test. The overall performance compares very favorably with that of equivalent-sized and larger catalytic thrusters.
- o Pulse-mode performance is considerably better than that typical of small catalytic hydrazine thrusters in terms of response times, pulse repeatability, and specific impulse. The minimum impulse bit capability is considerably better than state-of-the-art catalytic thrusters.
- o The reliability of the heater design for the EHT has been verified. No failures of the basic 30 ohm unit have been experienced in nearly 2 years of development.
- o Performance and life capability of the Parker valve design utilized for the program has been verified. No anomalies were experienced during the estimated 3×10^6 cycles accumulated on two units during development and the Engineering Model tests.
- o Haynes 25 proved sufficiently nitride-resistant to meet the performance and life goals of the program. With the substitution of noble metals in critical areas, it is believed that EHT life-time would be extended significantly.

- o Instrumentation and test techniques have been developed which are adequate for the direct measurement of the performance of hydrazine thrusters operating in the thrust range of 10 to 100 millipounds.

APPENDIX A

PULSE MODE TEST DATA (Data for Figure 4-9)

HYDRAZINE RESISTOJET THRUSTER TEST

TRW 01/1241

TIME OF DAY 15:33

UNIT S/N 235

REMARKS: 52.75, 100 152, 192, 1/5 ON, 1.6 SEC. GATE

00

0

0

0

0

-35

0

PULSE

PINJ
PSIATCH
DEG FWF
LBMI-BIT
LBF-SECPCN
PSIA-SECISP
SECC*
FT-SEC

CF

1535	0.361516E+03 0.961673E+01	0.144613E+04 0.159929E+03	0.230102E-04 0.383183E+04	0.367996E-02 0.134263E+01
1586	0.362371E+03 0.941847E+01	0.144877E+04 0.171365E+03	0.224022E-04 0.423252E+04	0.349623E-02 0.130249E+01
1537	0.362493E+03 0.931156E+01	0.144824E+04 0.177941E+03	0.196352E-04 0.434793E+04	0.349390E-02 0.121657E+01
1583	0.362860E+03 0.916905E+01	0.144824E+04 0.139693E+03	0.133682E-04 0.445543E+04	0.357917E-02 0.136966E+01
1589	0.363471E+03 0.921004E+01	0.144824E+04 0.138883E+03	0.133682E-04 0.447535E+04	0.356338E-02 0.135774E+01
1590	0.363226E+03 0.926707E+01	0.144982E+04 0.175213E+03	0.202954E-04 0.422306E+04	0.352097E-02 0.133314E+01
1591	0.363959E+03 0.939298E+01	0.144982E+04 0.171839E+03	0.202483E-04 0.425304E+04	0.348055E-02 0.130317E+01
1592	0.363226E+03 0.954132E+01	0.145034E+04 0.159942E+03	0.220896E-04 0.396019E+04	0.353304E-02 0.129926E+01
1593	0.363348E+03 0.957224E+01	0.144982E+04 0.170447E+03	0.213226E-04 0.411594E+04	0.363437E-02 0.133221E+01
1594	0.363715E+03 0.963038E+01	0.144982E+04 0.164697E+03	0.223964E-04 0.394240E+04	0.363862E-02 0.134393E+01
1595	0.363348E+03 0.953797E+01	0.145034E+04 0.171208E+03	0.216294E-04 0.404303E+04	0.370313E-02 0.136229E+01

1596	0.361394E+03 0.950517E+01	0.144771E+04 0.168030E+03	0.214760E-04 2.425791E+04	2.362362E-02 0.133212E+01
1597	0.361760E+03 0.931274E+01	0.144982E+04 0.162350E+03	0.219362E-04 0.339235E+04	2.356135E-02 2.134132E+01
1598	0.362738E+03 0.931633E+01	0.145287E+04 0.172476E+03	0.223624E-04 0.479427E+04	2.355654E-02 2.133949E+01
1599	2.362493E+03 0.930376E+01	0.145037E+04 0.172599E+03	2.274022E-04 2.413097E+04	0.343062E-02 2.131265E+01
1600	0.362615E+03 0.928593E+01	0.145140E+04 0.185115E+03	2.133632E-04 2.451223E+04	2.349279E-02 2.131973E+01
1601	0.363124E+03 0.930274E+01	0.145034E+04 0.173729E+03	2.196352E-04 2.434382E+04	2.352903E-02 2.132365E+01
1602	0.363226E+03 0.918962E+01	0.145034E+04 0.188036E+03	2.137143E-04 2.452222E+04	2.352322E-02 2.134431E+01
1603	2.362360E+03 0.926607E+01	0.145034E+04 2.186263E+03	2.194813E-04 2.436276E+04	0.362369E-02 2.137437E+01
1604	0.362360E+03 2.925415E+01	0.145034E+04 2.196146E+03	2.135614E-04 2.457111E+04	0.364075E-02 2.133341E+01
1605	0.363715E+03 0.933431E+01	0.145140E+04 0.173509E+03	2.212153E-04 2.427223E+04	2.353339E-02 2.134702E+01
1606	0.363959E+03 0.947960E+01	0.145140E+04 2.173388E+03	0.199420E-04 0.435332E+04	2.355742E-02 2.131673E+01
1607	0.363348E+03 2.965755E+01	2.145143E+04 2.162797E+03	0.223964E-04 2.395353E+04	0.363123E-02 2.132341E+01
1608	2.363837E+03 0.957904E+01	2.145140E+04 0.164729E+03	2.217328E-04 2.403185E+04	2.353327E-02 2.131437E+01
1609	0.364448E+03 2.950395E+01	0.145192E+04 0.163522E+03	0.222430E-04 0.391748E+04	0.363723E-02 2.134233E+01
1610	0.364204E+03 2.951729E+01	0.145192E+04 0.167134E+03	0.220396E-04 2.395222E+04	2.369303E-02 2.136152E+01
1611	0.361394E+03 0.929477E+01	0.145037E+04 0.166953E+03	0.207390E-04 2.411505E+04	2.345742E-02 2.132517E+01
1612	0.361633E+03 0.937751E+01	0.145140E+04 0.132586E+03	0.193234E-04 2.444323E+04	2.352912E-02 2.122046E+01
1613	0.361394E+03 0.929124E+01	0.145192E+04 2.176542E+03	2.204222E-04 2.417535E+04	2.362134E-02 2.136321E+01

1614	0.361760E+03 0.925073E+01	0.145140E+04 0.176372E+03	0.202433E-04 0.418362E+04	0.357739E-02 0.135693E+01
1615	0.361760E+03 0.923721E+01	0.145037E+04 0.187219E+03	0.137143E-04 0.452534E+04	0.350377E-02 0.133091E+01
1616	0.362615E+03 0.915737E+01	0.145140E+04 0.186530E+03	0.135614E-04 0.452316E+04	0.346041E-02 0.132071E+01
1617	0.361394E+03 0.141165E+02	0.151920E+04 0.206057E+03	0.273052E-04 0.474222E+04	0.500643E-02 0.139349E+01
1618	0.361633E+03 0.137968E+02	0.152139E+04 0.187912E+03	0.294523E-04 0.429436E+04	0.553452E-02 0.143752E+01
1619	0.361760E+03 0.133179E+02	0.152034E+04 0.190931E+03	0.283392E-04 0.430293E+04	0.550774E-02 0.139353E+01
1620	0.362615E+03 0.137369E+02	0.152139E+04 0.188753E+03	0.283392E-04 0.436713E+04	0.544343E-02 0.137041E+01
1621	0.362062E+03 0.133044E+02	0.152034E+04 0.200333E+03	0.260214E-04 0.435209E+04	0.517012E-02 0.134439E+01
1622	0.363343E+03 0.133154E+02	0.152191E+04 0.133103E+03	0.299132E-04 0.403447E+04	0.547732E-02 0.139111E+01
1623	0.363104E+03 0.141022E+02	0.152191E+04 0.185075E+03	0.297596E-04 0.434466E+04	0.550777E-02 0.137039E+01
1624	0.363471E+03 0.140729E+02	0.152191E+04 0.186494E+03	0.302193E-04 0.426961E+04	0.563533E-02 0.140517E+01
1625	0.363226E+03 0.142454E+02	0.152191E+04 0.184642E+03	0.306002E-04 0.425711E+04	0.566432E-02 0.139530E+01
1626	0.363593E+03 0.141938E+02	0.152244E+04 0.177535E+03	0.317533E-04 0.409026E+04	0.563743E-02 0.139359E+01
1627	0.364204E+03 0.143463E+02	0.152349E+04 0.175251E+03	0.319072E-04 0.412209E+04	0.559173E-02 0.136762E+01
1628	0.361760E+03 0.139942E+02	0.152191E+04 0.191153E+03	0.283392E-04 0.444399E+04	0.551262E-02 0.138213E+01
1629	0.361394E+03 0.138401E+02	0.152244E+04 0.173642E+03	0.319072E-04 0.397692E+04	0.554043E-02 0.140462E+01
1630	0.361332E+03 0.138648E+02	0.152297E+04 0.137427E+03	0.296062E-04 0.429366E+04	0.554399E-02 0.140423E+01
1631	0.361760E+03 0.140375E+02	0.152402E+04 0.139860E+03	0.294523E-04 0.436979E+04	0.559192E-02 0.139773E+01

1632	0.363226E+03 0.137920E+02	0.152455E+04 0.197166E+03	0.273052E-04 0.463103E+04	0.533364E-02 0.136964E+01
1633	0.362860E+03 0.139024E+02	0.152244E+04 0.195023E+03	0.280722E-04 0.454055E+04	0.547473E-02 0.138175E+01
1634	0.362860E+03 0.134330E+02	0.152402E+04 0.187392E+03	0.285324E-04 0.433255E+04	0.534675E-02 0.139142E+01
1635	0.363348E+03 0.137637E+02	0.152402E+04 0.178475E+03	0.306802E-04 0.411465E+04	0.547563E-02 0.139539E+01
1636	0.362982E+03 0.141403E+02	0.152455E+04 0.188969E+03	0.302193E-04 0.429006E+04	0.571060E-02 0.141703E+01
1637	0.362932E+03 0.141947E+02	0.152402E+04 0.179150E+03	0.316004E-04 0.411341E+04	0.566120E-02 0.139933E+01
1638	0.361271E+03 0.144295E+02	0.152507E+04 0.171494E+03	0.325203E-04 0.406305E+04	0.557714E-02 0.135617E+01
1639	0.362371E+03 0.144757E+02	0.152402E+04 0.175980E+03	0.320606E-04 0.413964E+04	0.564202E-02 0.136757E+01
1640	0.362127E+03 0.140230E+02	0.152402E+04 0.137605E+03	0.297596E-04 0.432025E+04	0.553306E-02 0.139697E+01
1641	0.362127E+03 0.133609E+02	0.152455E+04 0.182525E+03	0.303732E-04 0.418404E+04	0.554337E-02 0.143339E+01
1642	0.361760E+03 0.137453E+02	0.152560E+04 0.191403E+03	0.236353E-04 0.439322E+04	0.549263E-02 0.140161E+01
1643	0.362371E+03 0.140319E+02	0.152612E+04 0.134316E+03	0.299133E-04 0.431615E+04	0.552840E-02 0.137751E+01
1644	0.362982E+03 0.138515E+02	0.152612E+04 0.194338E+03	0.276120E-04 0.459932E+04	0.536605E-02 0.135930E+01
1645	0.363471E+03 0.140734E+02	0.152560E+04 0.191104E+03	0.286858E-04 0.449803E+04	0.548197E-02 0.136676E+01
1646	0.363104E+03 0.136770E+02	0.152507E+04 0.198173E+03	0.274586E-04 0.456677E+04	0.544169E-02 0.139604E+01
1647	0.361027E+03 0.189832E+02	0.156612E+04 0.186960E+03	0.417243E-04 0.417129E+04	0.780085E-02 0.144188E+01
1648	0.362005E+03 0.189402E+02	0.156454E+04 0.186167E+03	0.415714E-04 0.417722E+04	0.773923E-02 0.143373E+01
1649	0.362493E+03 0.189114E+02	0.156559E+04 0.190395E+03	0.401903E-04 0.431414E+04	0.765214E-02 0.141976E+01

1650	0.363104E+03 0.187306E+02	0.156717E+04 0.191097E+03	0.395772E-04 0.433913E+04	0.756312E-02 0.141673E+01
1651	0.363471E+03 0.185745E+02	0.156822E+04 0.192338E+03	0.394233E-04 0.431973E+04	0.758263E-02 0.143239E+01
1652	0.362982E+03 0.137361E+02	0.156322E+04 0.197085E+03	0.386563E-04 0.444374E+04	0.761366E-02 0.142677E+01
1653	0.363471E+03 0.184673E+02	0.156717E+04 0.202296E+03	0.382432E-04 0.445064E+04	0.769599E-02 0.146223E+01
1654	0.363104E+03 0.133922E+02	0.156770E+04 0.201025E+03	0.383502E-04 0.439707E+04	0.773931E-02 0.147075E+01
1655	0.361027E+03 0.185986E+02	0.156822E+04 0.195721E+03	0.388102E-04 0.439371E+04	0.759597E-02 0.143324E+01
1656	0.361271E+03 0.137451E+02	0.156875E+04 0.134731E+03	0.409578E-04 0.419612E+04	0.756321E-02 0.141664E+01
1657	0.361394E+03 0.137959E+02	0.156930E+04 0.137889E+03	0.423044E-04 0.422330E+04	0.756670E-02 0.143120E+01
1658	0.362615E+03 0.188059E+02	0.157138E+04 0.183713E+03	0.411112E-04 0.419402E+04	0.775824E-02 0.144752E+01
1659	0.363104E+03 0.188453E+02	0.157033E+04 0.187899E+03	0.414180E-04 0.417167E+04	0.773239E-02 0.144399E+01
1660	0.362493E+03 0.192506E+02	0.156980E+04 0.182933E+03	0.424913E-04 0.415370E+04	0.777313E-02 0.141679E+01
1661	0.363104E+03 0.187314E+02	0.156875E+04 0.192749E+03	0.397306E-04 0.433409E+04	0.765805E-02 0.143069E+01
1662	0.363593E+03 0.186736E+02	0.157033E+04 0.190263E+03	0.397306E-04 0.430922E+04	0.755925E-02 0.142039E+01
1663	0.360905E+03 0.183712E+02	0.156980E+04 0.211896E+03	0.362024E-04 0.465262E+04	0.767116E-02 0.146513E+01
1664	0.361271E+03 0.134120E+02	0.156930E+04 0.206613E+03	0.371228E-04 0.454733E+04	0.767007E-02 0.146168E+01
1665	0.361394E+03 0.185075E+02	0.157086E+04 0.196207E+03	0.389636E-04 0.435496E+04	0.764493E-02 0.144938E+01
1666	0.362982E+03 0.186908E+02	0.157086E+04 0.193799E+03	0.392704E-04 0.436375E+04	0.761055E-02 0.142370E+01
1667	0.362249E+03 0.188318E+02	0.157086E+04 0.187608E+03	0.406510E-04 0.424734E+04	0.762645E-02 0.142097E+01

1668	0.363104E+03 0.187907E+02	0.157191E+04 0.187046E+03	0.406510E-04 0.423807E+04	0.760360E-02 0.141981E+01
1669	0.363226E+03 0.189105E+02	0.157243E+04 0.185279E+03	0.417248E-04 0.415532E+04	0.773073E-02 0.143441E+01
1670	0.361027E+03 0.185332E+02	0.157243E+04 0.192623E+03	0.389636E-04 0.436101E+04	0.750527E-02 0.142092E+01
1671	0.361271E+03 0.186064E+02	0.157191E+04 0.193373E+03	0.380432E-04 0.448415E+04	0.756576E-02 0.142674E+01
1672	0.361760E+03 0.185612E+02	0.157191E+04 0.201645E+03	0.380432E-04 0.447328E+04	0.767121E-02 0.145015E+01
1673	0.362982E+03 0.183682E+02	0.157138E+04 0.211442E+03	0.362024E-04 0.465184E+04	0.765470E-02 0.146224E+01
1674	0.362615E+03 0.184054E+02	0.157138E+04 0.204897E+03	0.375830E-04 0.449003E+04	0.770264E-02 0.146804E+01
1675	0.363104E+03 0.186870E+02	0.157243E+04 0.196484E+03	0.391170E-04 0.437995E+04	0.763587E-02 0.144314E+01
1676	0.363104E+03 0.187778E+02	0.157243E+04 0.193447E+03	0.395772E-04 0.435007E+04	0.765608E-02 0.143059E+01
1677	0.363348E+03 0.188284E+02	0.157243E+04 0.185280E+03	0.409578E-04 0.421476E+04	0.758368E-02 0.141419E+01
1678	0.360538E+03 0.271144E+02	0.161822E+04 0.200438E+03	0.573716E-04 0.433311E+04	0.114995E-01 0.148810E+01
1679	0.361149E+03 0.272973E+02	0.161874E+04 0.198884E+03	0.587522E-04 0.425933E+04	0.116849E-01 0.150196E+01
1680	0.362738E+03 0.273565E+02	0.161874E+04 0.201113E+03	0.582920E-04 0.430277E+04	0.117236E-01 0.150368E+01
1681	0.363226E+03 0.272192E+02	0.161927E+04 0.193391E+03	0.582920E-04 0.428117E+04	0.115646E-01 0.149077E+01
1682	0.362982E+03 0.273778E+02	0.162032E+04 0.194047E+03	0.596726E-04 0.420648E+04	0.115793E-01 0.148402E+01
1683	0.360538E+03 0.271066E+02	0.162138E+04 0.204142E+03	0.567580E-04 0.437369E+04	0.115867E-01 0.149982E+01
1684	0.361394E+03 0.271345E+02	0.162295E+04 0.205173E+03	0.566046E-04 0.439508E+04	0.116137E-01 0.150177E+01
1685	0.362371E+03 0.271576E+02	0.162243E+04 0.204313E+03	0.564512E-04 0.441077E+04	0.115337E-01 0.149016E+01

1686	0.362982E+03 0.269373E+02	0.162295E+04 0.206648E+03	0.555303E-04 0.445533E+04	0.114753E-01 0.149195E+01
1687	0.363471E+03 0.269681E+02	0.162295E+04 0.202541E+03	0.567533E-04 0.435632E+04	0.114953E-01 0.149572E+01
1688	0.361394E+03 0.273179E+02	0.162243E+04 0.198363E+03	0.587522E-04 0.426304E+04	0.116334E-01 0.153365E+01
1689	0.361271E+03 0.273640E+02	0.162401E+04 0.198563E+03	0.532920E-04 0.430395E+04	0.115746E-01 0.143416E+01
1690	0.362615E+03 0.274421E+02	0.162506E+04 0.193790E+03	0.596726E-04 0.421637E+04	0.115639E-01 0.147357E+01
1691	0.361633E+03 0.275136E+02	0.162431E+04 0.194232E+03	0.596726E-04 0.422312E+04	0.115933E-01 0.147321E+01
1692	0.362982E+03 0.274660E+02	0.162348E+04 0.194453E+03	0.596726E-04 0.422003E+04	0.116033E-01 0.143239E+01
1693	0.360733E+03 0.271473E+02	0.162401E+04 0.204599E+03	0.561444E-04 0.443319E+04	0.114371E-01 0.143460E+01
1694	0.361332E+03 0.270061E+02	0.162506E+04 0.207565E+03	0.550706E-04 0.449611E+04	0.114307E-01 0.143514E+01
1695	0.362249E+03 0.263670E+02	0.162506E+04 0.207004E+03	0.553774E-04 0.444813E+04	0.114634E-01 0.149729E+01
1696	0.361760E+03 0.270734E+02	0.162506E+04 0.209246E+03	0.550706E-04 0.450732E+04	0.115233E-01 0.149345E+01
1697	0.363104E+03 0.271134E+02	0.162611E+04 0.200639E+03	0.581306E-04 0.427656E+04	0.116678E-01 0.150966E+01
1698	0.361149E+03 0.273140E+02	0.162716E+04 0.191762E+03	0.593260E-04 0.426256E+04	0.114723E-01 0.144725E+01
1699	0.361027E+03 0.273645E+02	0.162716E+04 0.193634E+03	0.593260E-04 0.427029E+04	0.115344E-01 0.145373E+01
1700	0.362493E+03 0.276610E+02	0.162664E+04 0.197607E+03	0.582920E-04 0.435065E+04	0.115139E-01 0.146117E+01
1701	0.362360E+03 0.274161E+02	0.162822E+04 0.199550E+03	0.573716E-04 0.438132E+04	0.114485E-01 0.146520E+01
1702	0.362738E+03 0.274430E+02	0.162927E+04 0.202207E+03	0.575250E-04 0.437392E+04	0.116320E-01 0.143722E+01
1703	0.361271E+03 0.272336E+02	0.162822E+04 0.193873E+03	0.573313E-04 0.432545E+04	0.115012E-01 0.147909E+01

1704	0.361633E+03 0.273585E+02	3.162769E+04 0.201563E+03	0.573716E-04 0.437210E+04	0.115640E-01 0.148312E+01
1705	0.361832E+03 0.273876E+02	0.162322E+04 0.196546E+03	0.592124E-04 0.424070E+04	0.116330E-01 0.149133E+01
1706	0.362738E+03 0.274268E+02	0.162322E+04 0.198294E+03	0.539256E-04 0.426383E+04	0.116330E-01 0.149433E+01
1707	0.362932E+03 0.274673E+02	0.162927E+04 0.199929E+03	0.539256E-04 0.427527E+04	0.117769E-01 0.150443E+01
1708	0.362172E+03 0.340533E+02	0.164821E+04 0.209951E+03	0.727174E-04 0.441493E+04	0.143472E-01 0.152932E+01
1709	0.362127E+03 0.341607E+02	0.165032E+04 0.207206E+03	0.719446E-04 0.435336E+04	0.149274E-01 0.153119E+01
1710	0.362615E+03 0.345093E+02	0.165032E+04 0.224646E+03	0.723650E-04 0.434224E+04	0.149116E-01 0.151615E+01
1711	0.362615E+03 0.345634E+02	0.165137E+04 0.200330E+03	0.742456E-04 0.426817E+04	0.149735E-01 0.151346E+01
1712	0.360905E+03 0.340695E+02	0.165420E+04 0.209613E+03	0.725640E-04 0.442668E+04	0.147911E-01 0.152332E+01
1713	0.361633E+03 0.339180E+02	0.165453E+04 0.203137E+03	0.711776E-04 0.436901E+04	0.143133E-01 0.153293E+01
1714	0.362249E+03 0.342777E+02	0.165553E+04 0.208738E+03	0.717912E-04 0.437761E+04	0.149336E-01 0.153397E+01
1715	0.360905E+03 0.344006E+02	0.165663E+04 0.196596E+03	0.753194E-04 0.413751E+04	0.143075E-01 0.151032E+01
1716	0.361832E+03 0.345212E+02	0.165611E+04 0.202623E+03	0.737854E-04 0.428954E+04	0.149510E-01 0.151963E+01
1717	0.361832E+03 0.346734E+02	0.165611E+04 0.220286E+03	0.743592E-04 0.424665E+04	0.149932E-01 0.151724E+01
1718	0.360661E+03 0.341301E+02	0.165663E+04 0.206227E+03	0.713310E-04 0.433637E+04	0.147104E-01 0.151232E+01
1719	0.361760E+03 0.340393E+02	0.165663E+04 0.210571E+03	0.697970E-04 0.447143E+04	0.146972E-01 0.151497E+01
1720	0.361760E+03 0.339746E+02	0.165663E+04 0.210737E+03	0.725640E-04 0.441435E+04	0.143704E-01 0.153577E+01
1721	0.360172E+03 0.344401E+02	0.165663E+04 0.199604E+03	0.740922E-04 0.426175E+04	0.147391E-01 0.150672E+01

1722	0.361638E+03 0.344845E+02	0.165663E+04 0.202521E+03	0.731713E-04 0.432092E+04	0.143188E-01 0.152730E+01
1723	0.362493E+03 0.344974E+02	0.165769E+04 0.202922E+03	0.733252E-04 0.431350E+04	0.148793E-01 0.151339E+01
1724	0.361516E+03 0.340637E+02	0.165874E+04 0.206718E+03	0.711776E-04 0.433842E+04	0.147137E-01 0.151533E+01
1725	0.361638E+03 0.342023E+02	0.165663E+04 0.209904E+03	0.702572E-04 0.446334E+04	0.147473E-01 0.151290E+01
1726	0.362615E+03 0.341290E+02	0.165663E+04 0.210775E+03	0.702572E-04 0.445378E+04	0.143034E-01 0.152244E+01
1727	0.360661E+03 0.344397E+02	0.165663E+04 0.202817E+03	0.734736E-04 0.429729E+04	0.149327E-01 0.151831E+01
1728	0.361149E+03 0.342737E+02	0.165769E+04 0.203006E+03	0.730184E-04 0.430353E+04	0.143231E-01 0.151752E+01
1729	0.362005E+03 0.342482E+02	0.165769E+04 0.201467E+03	0.736320E-04 0.426449E+04	0.148344E-01 0.151980E+01
1730	0.360733E+03 0.341538E+02	0.165716E+04 0.205399E+03	0.722514E-04 0.433400E+04	0.148765E-01 0.152832E+01
1731	0.361516E+03 0.341265E+02	0.165769E+04 0.203440E+03	0.714844E-04 0.437700E+04	0.149002E-01 0.153199E+01
1732	0.361760E+03 0.341095E+02	0.165716E+04 0.209028E+03	0.710242E-04 0.440317E+04	0.148460E-01 0.152718E+01
1733	0.360783E+03 0.340935E+02	0.165716E+04 0.203558E+03	0.713310E-04 0.438216E+04	0.143766E-01 0.153105E+01
1734	0.361149E+03 0.342234E+02	0.165769E+04 0.209418E+03	0.716378E-04 0.433003E+04	0.150022E-01 0.153811E+01
1735	0.361760E+03 0.343548E+02	0.165663E+04 0.204992E+03	0.733252E-04 0.429566E+04	0.150311E-01 0.153518E+01
1736	0.359928E+03 0.341689E+02	0.165663E+04 0.202355E+03	0.733252E-04 0.427242E+04	0.143377E-01 0.152367E+01
1737	0.362005E+03 0.337621E+02	0.165821E+04 0.203800E+03	0.707174E-04 0.437723E+04	0.147658E-01 0.153455E+01